

THE STUDY OF ROCKS

by S. J. Shand

EARTH LORE : GEOLOGY WITHOUT JARGON

ERUPTIVE ROCKS

USEFUL ASPECTS OF GEOLOGY

THE STUDY OF ROCKS

by

S. J. SHAND

D.Sc., Ph.D., F.G.S.

*Newberry Professor of Geology
in Columbia University, New York*

17092

Second Edition

Revised and Enlarged



552

Sha

LONDON

THOMAS MURBY & CO

40, MUSEUM STREET, W.C.1.

FIRST PUBLISHED IN
1931
SECOND EDITION REVISED
1947

**CENTRAL ARCHAEOLOGICAL
LIBRARY, NEW DELHI.**

Acc. No. 17692
Date. 20.10.59
Call No. 552/sha
.....

All rights reserved

PRINTED IN GREAT BRITAIN
In 10 point Old Style Type
BY THE WOODBRIDGE PRESS, LTD,
GUILDFORD

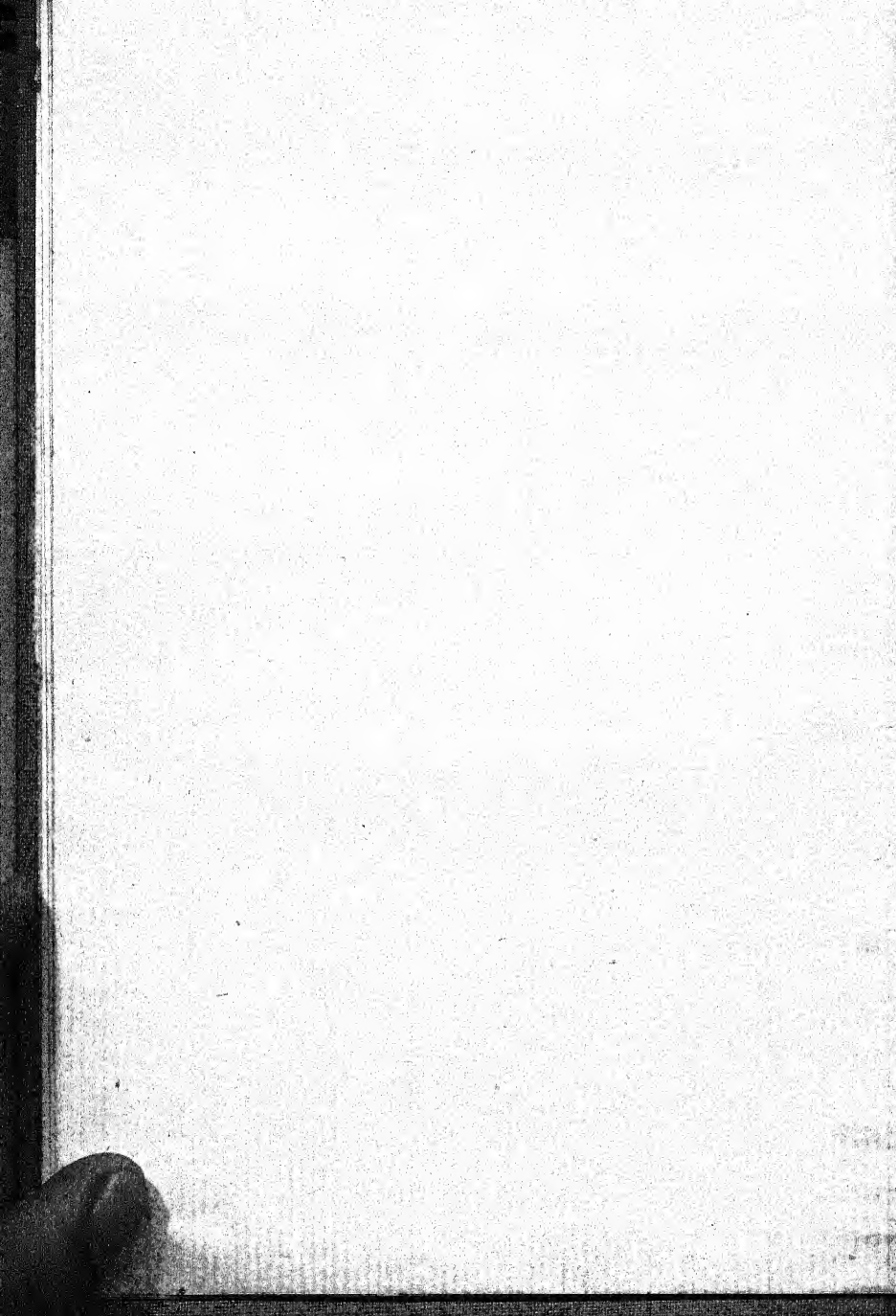
Recd from Labrador Brook Station, N. B. 19/10/57 29/10/60

In the present state of petrographical nomenclature the student will be saved much trouble if he will fix his attention on the rocks themselves instead of on the names which have been used in different senses by different writers.

J. J. H. TEALL

Geologists should use their mother tongue whenever it can be made to serve, and usually it will be found rich enough to express all the ideas they may have, instead of searching the dictionaries of the dead languages for more or less accurate translations of plain English terms.

ISRAEL C. RUSSELL



CONTENTS

CHAPTER I

THE STUDY OF ROCKS

	PAGE
Field observations	1
Laboratory examination	3
Desirability of chemical analysis	4
Summary of procedure	6

CHAPTER II

ERUPTIVE ROCKS IN THE FIELD

Intrusive and extrusive rocks	9
Characters of lava-flows	10
Characters of minor intrusions	12
Characters of major intrusions	16
Manner of emplacement	19

CHAPTER III

THE COMPOSITION OF ERUPTIVE ROCKS

Solid solution	22
The feldspar family	23
The metasilicate family (pyroxenes and amphiboles)	25
The mica family	27
The tourmaline family	27
The olivine family	28

	PAGE
The nepheline family	28
Leucite and analcime	29
The garnet family	29
The melilite family	30
The epidote family	30
The silica group	31
Minor constituents	31
The relative abundance of various minerals and oxides	33

CHAPTER IV

THE CLASSIFICATION OF ERUPTIVE ROCKS

The species concept	37
Ferdinand Zirkel	38
H. Rosenbusch	38
Alfred Harker	40
F. H. Hatch	42
Joseph P. Iddings	43
W. Cross, J. P. Iddings, L. V. Pirsson and H. S. Washington	45
Paul Niggli	46
A. Johannsen	48
S. J. Shand	49
A. Lacroix	54
Summary	55

CHAPTER V

ERUPTIVE ROCKS: THE OVERSATURATED CLASS

Content and subdivision	57
Geological occurrence	60
Mineralogy and texture	63
The eucrystalline division	68
The dyscrystalline division	73

CHAPTER VI

ERUPTIVE ROCKS : THE SATURATED CLASS

	PAGE
Content and subdivision	79
Geological occurrence	84
Mineralogy and texture	88
The orthoclase division	91
The plagioclase division	95
The hypermelanic division	99

CHAPTER VII

ERUPTIVE ROCKS : THE UNDERSATURATED CLASS
(NON-FELDSPATHOIDAL GROUP)

Content and subdivision	102
Geological occurrence	103
Mineralogy and texture	108
The orthoclase division	109
The plagioclase division	110
The hypermelanic division	113

CHAPTER VIII

ERUPTIVE ROCKS : THE UNDERSATURATED CLASS.
(FELDSPATHOIDAL GROUP)

Content and subdivision	115
Geological occurrence	117
Mineralogy and texture	118
Rocks containing leucite	123
Rocks not containing leucite	125
	I

CONTENTS

CHAPTER IX

SEDIMENTARY ROCKS

	PAGE
Sedimentary rocks in the field	130
The composition of sedimentary rocks	135
The classification of sedimentary rocks	139

CHAPTER X

SEDIMENTARY ROCKS, CLASS I : ORGANIC RESIDUES

Limestone and dolomite	142
Guano, phosphorite and bone-breccia	146
Diatomaceous and radiolarian earths	147
Peat, coal and oil-shale	148

CHAPTER XI

SEDIMENTARY ROCKS, CLASS II : RESIDUES FROM SOLUTION

Calc-sinter and oolite	151
Ironstone	155
Siliceous sinter, chert, jasper	157
Anhydrite and gypsum	158
Rock salt and other salts	161

CHAPTER XII

SEDIMENTARY ROCKS, CLASS III : CRYSTALLINE ROCK-RESIDUES

Breccia and tillite	163
Agglomerate and tuff	165
Conglomerate	167
Grit, arkose and greywacke	169
Sandstone and quartzite	170
Siltstone and loess	172

CHAPTER XIII

SEDIMENTARY ROCKS, CLASS IV: CRYPTOCRYSTALLINE AND
COLLOIDAL ROCK-RESIDUES

	PAGE
Clay, mudstone, shale, slate	174

CHAPTER XIV

METAMORPHIC ROCKS

Metamorphic rocks in the field	179
Mylonite and pseudo-tachylyte	180
Hornstones	182
Crystalline schists	184
The special minerals of metamorphic rocks	187
The classification of metamorphic rocks	190

CHAPTER XV

METAMORPHIC ROCKS: DESCRIPTION

Class I. Mylonites	198
Class II. Hornstones, quartzites and marmorites	200
Class III. The crystalline schists	206
Peraluminous type	207
Metaluminous type	210
Subaluminous type	214
Peralkaline type	216

APPENDIX

THE CHEMICAL ANALYSIS OF ROCKS	218
INDEX	230



CHAPTER I.

THE STUDY OF ROCKS.

The study of rocks should be begun in the field, carried on under the microscope, and finished in the crucible. All three methods of study—geological, mineralogical and chemical—are needed to give the fullest possible insight into the nature and history of a rock. In practice the chemical method is often neglected, on the plea that the main chemical characters of a rock can be gathered accurately enough from its mineralogical composition; but in all thorough petrographical work chemical analysis is used to confirm and extend the conclusions drawn from microscopic study. In short, what the petrographer cannot learn through the microscope he should be prepared to seek in the crucible.

In the field one observes the habit of a rock as a mass, that is to say, its shape, its size, and its relation to other rocks near it; and decides whether it is of eruptive or sedimentary origin; notes any variation of texture or composition between one part and another, and any changes that take place near the contacts with other rocks; records the presence of enclosures or segregations, and the directions of joints, bedding-planes, partings, and planes of shearing or flow. If the field observation has been thorough, then the petrographer should come to the microscopic examination of the rock with definite knowledge of the following matters:—

- (1) Whether the rock was formed under eruptive or sedimentary conditions;
- (2) If eruptive, whether it is intrusive or extrusive; the form and size of the mass; whether it is

homogeneous or not; and in the latter event, what relation the specimen to be examined bears to the main mass (that is, whether it is an average sample, a coarse-grained facies, a basic variety, a chilled marginal facies, etc., etc.);

- (3) If sedimentary, its geological age and relations; whether it is fossiliferous or not; whether it has been subjected to compression or heating since its formation;
- (4) If the rock is a metamorphic one, whether the metamorphism was thermal or regional; how the rock changes as it is traced along the strike; whether the structure suggests an eruptive, sedimentary or mixed origin;
- (5) In any case, whether the samples taken for microscopic study are as fresh as possible and are thoroughly representative of the rock-mass as a whole.

Petrology is too often made to appear as if it were a study of rock specimens instead of a study of rocks. The principle we have to grasp is that *petrography may be done in the laboratory but petrology must be learned in the field*. To illustrate the pitfalls into which a petrographer may be led who studies a rock in the laboratory without knowing its field-relations, we may cite the following cases.

As a result of bad observation in the field, crush-bands in granite have been mistaken for grits; coarse eruptive breccias for normal eruptive rocks; recrystallized tuffs for fine-grained lavas; metamorphic rocks for eruptive ones; and foreign crystals picked up and enclosed by the magma have been thought to be early crystallizations from the magma. In consequence of bad sampling, it has often happened that rare and quantitatively unimportant facies of a rock-mass have been described as if they composed the whole of it, as in the well-known instance of "rockallite." This name was given to a single small specimen of rock from the islet of Rockall, under the im-

pression that it formed the whole rock-mass; later investigation showed that the so-called rockallite only forms small nodules within a very different type of rock. There is a common tendency to collect unusual-looking rocks rather than familiar-looking ones, with the result that rare and what one might call pathological rock-varieties occupy an undeserved amount of space in the literature of petrology.

Failure to collect the freshest possible samples of the rock makes the identification of some minerals very difficult, and it may cause one to overlook altogether a readily-decomposed mineral such as nepheline or melilite. A confusion between primary and secondary characters is also possible in this case.

When the field work is done and the specimens have been brought in to the laboratory, the petrologist will generally proceed to make thin sections for study under the microscope. It is very important that every student should learn how to make his own rock sections. The technique is simple and the materials cost so little that there is no excuse, on the ground either of difficulty or of expense, for neglecting to learn this essential part of the petrographer's craft. It is most instructive to see for oneself how minerals change their appearance, as regards colour, pleochroism and chromatic polarization, as they are ground thinner and thinner. Feebly pleochroic minerals like andalusite are easily recognized while the section is still thick; and minerals which differ little in birefringence, such as microcline and albite, may be clearly distinguished if the grinding is stopped when one of them is grey and the other still shows a faint yellow colour between crossed nicols. Again, some minerals are easily identified by treating the section with acid before the cover-glass is put on; if one buys ready-made sections it is necessary to remove the cover-glasses before such tests can be applied. There is also the important consideration that the petrologist who can make his own thin sections does not need to interrupt his

work for days or even weeks at a time while waiting for sections to be prepared for him by a lapidary.

The properties of the rock-forming minerals, and the method of using the polarizing microscope, are described in so many excellent text-books that there is no need to repeat them here. It must be emphasised that the examination of a rock is not finished when one has named the minerals seen under the microscope. It is often desirable to measure their relative proportions by weight or volume. For this purpose one may use a stage- or eyepiece-micrometer in conjunction with the microscope, or he may carry out an actual separation of the various kinds of grains by means of heavy liquids such as bromoform, methylene iodide, and Clerici's solution. The latter method may also be used to isolate a few grains of an unknown mineral for the purpose of determining its specific gravity, its refractive index, or for spectroscopic analysis. Great importance is attached, in sedimentary petrography, to the correct determination of rare accessory constituents such as xenotime, allanite, stauroilite, barytes, for these give a simple means of distinguishing between similar-looking rocks which come from different horizons. In addition to such determinations of the properties of individual minerals, the specific gravity of the rock as a whole should be measured, either in the lump, using a Walker balance, or on crushed grains, by the pycnometer method. In dealing with a glassy rock one should not omit to determine both the specific gravity and the refractive index of the glass.

Having established as much as he can about the rock and its constituent minerals by the methods indicated above, the petrographer must now decide whether a chemical analysis of the rock is required to complete his investigation. If the rock is very fine-grained or glassy, or if for any other reason doubt remains as to its precise mineralogical composition, then chemical analysis is called for. Sometimes a partial analysis—say a determination of potash and soda—will suffice to resolve the

doubt and permit the rock to be classified correctly. But a complete analysis is always more satisfactory than a partial one, because it provides a check on the accuracy of the microscopic work. For instance, if a rock is said to contain nepheline but the analysis shows more than seventy per cent. of silica; or if much apatite is reported but no phosphoric acid is found by the analyst, then it is clear that a mistake has been made by somebody.

To make a complete quantitative analysis of a rock, which means determining at least three acidic and seven or eight metallic radicles, is a lengthy and tedious business requiring one's constant attention for a week or ten days, according to one's skill and facilities. It is not surprising that few petrologists care to undertake this work themselves, preferring either to do without chemical data or to enlist the help of a professional chemist; but it is most desirable that students of rocks should be able to make their own analyses if necessary. Many a fine piece of petrological research has been left incomplete because the student lacked the skill or the facilities for making the necessary analyses and was unable to secure the assistance of a chemist. It is in the hope of enticing some students of petrology to practise the difficult but fascinating art of rock-analysis that a condensed account of the procedure is given in an appendix to this book.

The analysis done, one should not be content with a bald statement of the oxides found and their proportions by weight. He should calculate the molecular proportions of the various oxides and radicles, by dividing percentage by molecular weight in each case. It will then be possible to combine the radicles, on paper, in such a way as to ascertain the possible proportions of orthoclase, albite, anorthite, quartz and other simple molecules which the rock may contain, and to get a valuable indication of the composition of more complex minerals such as hornblende and pyroxene, if these are present. Used in this way, the chemical analysis both checks and supplements

the microscopic work and gives one the fullest knowledge of the chemical character of the rock.

But it is not the highest aim of petrology to accumulate volumes of mineralogical and chemical data about rocks. These are means to an end, which is the understanding of the physical and chemical changes that take place beneath the crust of the earth. That basalt occurs here and granite there matters little to anybody; but *why* one region should be formed of magnesian rocks and another of sodic or potassic ones is one of the biggest of all geological problems. It is bound up on one hand with the origin of continents and oceans and mountain-ranges, and on the other hand with the distribution of gold, copper, tin, platinum and other useful substances. These grand problems will not be solved by any sudden flash of inspiration or stroke of luck, but only by the combination of thousands of seemingly unimportant and unrelated observations made by petrologists working in the field and in laboratories all over the world.

SUMMARY

OF THE PROCEDURE FOLLOWED IN THE EXAMINATION OF A ROCK.

- I. *Field study.* Observe geological occurrence, form and size of mass; whether homogeneous or variable, and nature of variation; note large structures such as bedding, jointing, crushing, shearing, enclosures, concretions; effects of weathering or metamorphism. Collect representative specimens.
- II. *Megascopic examination.* Identify the constituent minerals as far as possible. Determine the specific gravity of the rock. If the rock is largely glassy, determine the specific gravity and refractive index of the glassy portion.

- III. *Examination of thin sections under the microscope.* Determine all minerals present as fully as possible, using staining methods and microchemical tests when necessary. Measure the relative proportions of the various minerals by means of a micrometer, preferably of the recording or integrating type. Observe the mutual relations of minerals, *i.e.*, enclosure of one mineral in another, reaction rims, etc.
- IV. *Examination of crushed grains.* To supplement the microscopic examination, if necessary, crush some of the rock to grains of suitable size and separate by means of heavy fluids, electromagnet, or by hand picking. Individual grains may then be examined for specific gravity or refractive index, or submitted to microchemical tests or spectroscopic analysis. Proportions of minerals may be ascertained by weighing the separated fractions.
- V. *Chemical examination.* This may be partial or complete, according to the needs of the case. From the analytical data the mineralogical composition of the rock should be calculated and compared with the result obtained by the microscopic method.

WORKS OF REFERENCE.

The principal works of reference in the English language on the methods of practical petrography are

- A. HOLMES, *Petrographic Methods and Calculations* (London, T. Murby & Co.).
- A. JOHANNSEN, *Manual of Petrographic Methods* (New York, McGraw-Hill Co.).
- H. B. MILNER, *Sedimentary Petrography* (London, T. Murby & Co.).
- H. S. WASHINGTON, *The Chemical Analysis of Rocks* (New York, Wiley & Sons).
- A. F. ROGERS and P. F. KERR, *Optical Mineralogy* (New York, McGraw-Hill Co.).

- A. N. WINCHELL, *Elements of Optical Mineralogy* (New York, Wiley & Sons).
H. G. SMITH, *Minerals and the Microscope* (London, T. Murby & Co.).
J. W. EVANS, *The Determination of Minerals under the Microscope* (London, T. Murby & Co.).

Students should take the earliest opportunity of making themselves familiar with the two German classics of petrography,

- F. ZIRKEL, *Lehrbuch der Petrographie*, and
H. ROSENBUSCH, *Mikroskopische Physiographie der Mineralien und Gesteine*.

CHAPTER II.

ERUPTIVE ROCKS IN THE FIELD.

Eruptive or igneous rocks are those which have been formed by the cooling of a hot siliceous liquid from a temperature which was probably in every case above 500° Cg. When we see such a liquid at the earth's surface, in the crater of an active volcano or flowing down its slopes, we call it "lava"; but geologists have a more general term, *rock magma*, which is free from certain misconceptions which have grown around the word lava. The source of rock magma is in the deeper levels of the lithosphere, perhaps twenty miles or more beneath the surface. From this source tongues of magma rise along fissures in the solid earth-crust, and coming to regions of lower temperature and pressure, gradually suffer such a loss of heat and of dissolved gases that the magma congeals or "freezes." There arise in this way *intrusive* rocks, formed by magma which cooled before it reached the surface, and *extrusive* or *volcanic* rocks, formed by magma which was discharged upon the surface from a volcanic vent.

Each of these groups may be further subdivided, as follows :—

- | | |
|------------------|--|
| Extrusive | { (a) Fragmental volcanic rocks (tuffs). |
| | { (b) Lava-flows. |
| Intrusive | { (a) Minor intrusions (dyke rocks). |
| | { (b) Major intrusions (plutonic rocks). |

The volcanic fragmental rocks or *tuffs* form a transitional group between normal eruptive rocks and sediments. They are composed of fragments of lava and

other rocks, not all of which are necessarily igneous, thrown out by active volcanoes and spread over the surrounding lands or the sea-floor. In mineralogical and chemical constitution tuffs are often similar to lavas, but their geological behaviour is so typically sedimentary that they will not be considered further in this section.

The term *lava* is applied both to the hot liquid magma and to the cold solid rocks which are formed when the magma freezes. It is mostly in the latter sense that the term will be used here. A body of lava may have the form of a cylindrical plug, when it occupies the actual throat of a volcano, or of more or less parallel-sided sheets (lava-flows) which are interbedded with layers of tuff and sedimentary rocks. It is often a difficult matter to distinguish between a true lava-flow, which has been covered up by sediment, and an intrusive sheet which has been squeezed in along the bedding-planes of a sedimentary series without reaching the surface. The points to be observed in attempting to make such a distinction are

- (1) whether the upper surface of the sheet is compact or vesicular;
- (2) whether the sheet shows chilled margins both above and below or only below;
- (3) whether both roof and floor, or floor only, show signs of baking or metamorphism;
- (4) whether fragments of the roof are enclosed in the sheet;
- (5) whether veinlets from the sheet cut the roof.

The presence of gas-vesicles, which may be empty or filled with secondary minerals (agate, calcite, zeolites, etc.), is characteristic of lava-flows, especially in their upper parts. The central part of a thick flow may be quite free from vesicles while the top of the sheet and sometimes the bottom too are highly vesicular or slaggy. It is possible that gas vesicles may also form in an intrusive sheet which has been injected beneath a very light cover of sediment.

Most lavas consist partly of glass and partly of crystals, although on one hand the glass may be almost lost to sight in the interstices of the crystals and on the other hands the crystals may be so minute as to be invisible until the rock is examined under the microscope. Porphyritic texture is rather common in lavas: that is, a number of relatively large crystals are developed in a minutely crystalline or glassy groundmass. These large crystals are often called "phenocrysts," but the writer prefers to call them "insets," on the principle that a good English word is preferable to a bad Greek one. One must be careful to distinguish between real insets, which are crystallizations from the magma, and foreign grains picked up by the magma, or secondary minerals such as quartz and calcite which were introduced into gas-vesicles after the lava had become solid.

A streaky or banded appearance due to movement of the congealing mass is often observed in lava. Some of the bands may be more porous than others, and these are generally more deeply oxidized and so differently coloured from the denser bands; or else stony bands, consisting largely of spherulitic crystals, will alternate with glassy bands, again giving rise to a conspicuous difference in colour. A later movement than that which caused the flow-banding, taking place when the lava has become extremely viscous, may produce contortion and puckering of the bands, which may even be thrown into concertina-like folds.

Cryptocrystalline and spherulitic textures are products of very imperfect crystallization. In the former case the rock is crystalline but on such a minute scale that the grains can not be separately distinguished under the microscope. Spherulitic texture develops in glassy lavas by the initiation of centres of crystallization at relatively few points, from which delicate fibres of quartz and feldspar grow out in all directions, producing little spheroidal bodies with radial-fibrous structure. Spherulites in lava may be as much as an inch in diameter, or

they may be wholly microscopic. Similar bodies are often developed in badly annealed commercial glass.

Among *Intrusive Rocks* the best-known forms are the pipe, the dyke and the sill. A *pipe* is a more or less cylindrical body of rock which occupies the supply-channel of a former volcano; its upward termination is a volcanic plug. A *dyke* is a parallel-sided sheet which cuts across the principal structural planes (bedding-planes, cleavage-planes, etc.) of the country rocks; a *sill* is a sheet injected along the principal structural planes. Thus a dyke is not necessarily vertical or a sill horizontal; the point of difference between them is the transgressive attitude of one and the concordant attitude of the other. Besides the ideal dyke with parallel walls, there is a type of transgressive intrusion which is better described as a *wedge* or *wedgedyke*. The edge of the wedge is turned upwards and the outcrop on a level surface is dykelike, but the sides of the wedge diverge downwards, one side being generally concordant to the country rocks and the other transgressive.

The most thoroughly investigated examples of pipes are those composed of very basic rocks. Such are the diamond-bearing "kimberlite" pipes of South Africa and the smaller pipes of platinum-bearing peridotite in the eastern Transvaal, which have been deeply explored in mining operations. The pipe which has become the Premier diamond mine is nearly a thousand yards in diameter; the Kimberley pipe is six hundred feet across; but most pipes are much smaller than these. They descend vertically or very steeply, and become narrower as they are followed downwards, but no pipe has been explored down to its root or origin. The greatest depth reached in the Kimberley mine was 3,600 feet. The diamond pipes have been shown in several instances to be situated at the intersection of two dykes, or else to be local swellings in the course of a dyke; these conclusions are probably applicable to all pipes. The linear arrangement of volcanoes, and their frequent location at the

junctions of two sets of intersecting lines, follow naturally from this relation of pipes to dykes.

Sills and dykes may be of any dimensions from a few centimetres up to half a mile or more in width, and from a few feet up to scores of miles in extension. Dykes tend to occur in swarms, those of one swarm either being parallel (the commonest condition) or else radiating in all directions from a common centre. Superb illustrations of parallel dyke systems will be found on geological maps of the west of Scotland (Argyll, Mull, Inverness) and of radial swarms in the Cheviot Hills, Scotland; Spanish Peak, Colorado; and the Crazy Mts., Montana.

Some dykes are composite, that is, they consist of two or more quite different kinds of rock, one kind occupying the centre of the dyke with the other or others marginal to it. Such a composite dyke may result from successive infillings of an intermittently opened fissure, or from differential movement in the magma by which the early-formed crystals are swept to the sides of the fissure. All small intrusions tend to show "chilled margins" of finer grain than the rest of the rock, and basaltic dykes often have a thin selvage of basalt glass on each side.

Sills as well as dykes may be composite, but in this case the change takes place from top to bottom. Many thick sills are enriched with pyroxene, olivine and other heavy grains towards the base, and with feldspar and quartz towards the top, apparently in consequence of the sinking of early-formed crystals and the rise of a siliceous liquid residue. Instances of such phenomena are always worthy of detailed study, for what happens in a sheet of magma only a few hundred feet thick may be supposed to happen on a much greater scale in deeper levels of the earth-crust.

Dyke-rocks (using this term in the Rosenbuschian sense, to cover all rocks that occur in minor intrusions) are typically better crystallized than lavas, but every stage is represented between purely glassy rocks and completely crystalline, very coarse-grained ones. For this reason

the distinction of "dyke-rocks" from plutonic rocks and lavas is a geological rather than a petrological distinction. Many dyke-rocks are porphyritic, large insets of feldspar being particularly common. While it is often true that the largest intrusions are the most perfectly crystallized, and that narrow dykes tend to be glassy, this is no invariable rule. Dykelets of pegmatite only a few millimetres wide may be completely and coarsely crystalline, while a body of porphyry scores of feet in diameter may have a cryptocrystalline groundmass. The completeness of crystallization and the size of the crystals (the *crystallinity* and the *granularity* of the rock) seem to depend more upon the rate of loss of the fugitive constituents of the magma, consisting of water and dissolved gases and salts, than upon the rate of cooling. These volatile substances with small molecules seem to play the part of catalysts, helping to build up the large, complicated molecules of the aluminosilicate minerals, and in their absence the latter often fail to crystallize.

A dyke which cuts a larger body of eruptive rock may have sharp margins or it may grade imperceptibly into the surrounding rock. In the former case the dyke was clearly injected after the country rock had finished its crystallization; in the latter case the two rocks may be of almost the same age, one being the residual liquor from the crystallization of the other. When two dykes or a dyke and a sill intersect, it is generally possible to say which is the younger of the two by observing the presence of broken crystals, enclosures, flow-lines or chilled margins. The observation may have an important bearing on the history of an eruptive province.

Dykes and sills are always well jointed in directions perpendicular to the bounding walls. With several sets of joints, the whole mass may break up into prismatic columns, as many basaltic lavas do. Sometimes the contraction of the cooling mass of magma has been so great that wide transverse fissures were formed which were afterwards filled by material different from that of the

main body. Thus granitic dykes are sometimes crossed by "ladder veins" of white quartz; and basic sills may show transverse dykelets of pegmatitic or feldspathic nature.

We have spoken of a sill as a parallel-sided sheet. In reality every sill must thin out and eventually come to an end, so the actual form is that of an extremely flat lens. When the convexity of the lens is greater than usual, then we get a type of intrusion which has been called a *laccolith* or stone-cistern. The ideal laccolith has the shape of a plano-convex lens—or simply a lentil—with a more or less flat floor and a domed roof. If the channel through which the magma entered is in the floor of the laccolith, then the whole thing should have a rough resemblance to a mushroom with its stalk; but as the supply-channel is more likely to be a dyke than a pipe the mushroom analogy is not a very good one. The essential point which differentiates a laccolith from an ordinary sill is the rapid increase in thickness from margin to centre, and the consequent raising of the sedimentary roof in the form of a dome or blister. The ratio of thickness to horizontal extension in some of the laccoliths of the Henry Mountains is one to seven; in Shonkin Sag it is one to forty; in the average sill it is one to many hundreds. The roof of a laccolith is often well preserved, but laccoliths which allow any part of their floor to be seen are uncommon. One of the most complete examples is the Shonkin Sag laccolith in the Highwood Mts. of Montana, which is beautifully exposed in a natural cross-section showing both roof and floor. The maps, drawings, and photographs of this laccolith, by J. D. Barksdale and by C. S. Hurlbut, deserve careful study.

Laccoliths, like thick sills, are often strongly differentiated, the lighter minerals being concentrated towards the roof and the heavier ones towards the floor. Shonkin Sag shows a "chilled margin" of dark, porphyritic rock all round; but within this shell the rock is a coarse-grained mixture of feldspar (light) and pyroxene (heavy),

showing a concentration of feldspar about the centre of the mass.

The *phacolith* might be described as a saddle-shaped laccolith; it is a possible intrusion-form among sedimentary beds which have been folded into synclines and anticlines; but there is this important difference between a laccolith and a phacolith that the former is the cause of the folding of its country rocks while the latter is a consequence of folding. The Corndon sheet in Shropshire and the Aletsch and St. Gotthard masses in the Alps have been described as phacoliths. The type has recently been recognized in the Adirondack Mts. of New York; the phacoliths are of granite, and are two to fifteen miles long.

The *lopolith* is a saucer-shaped intrusive body occupying a tectonic basin. The disposition of the roof is immaterial; it may be horizontal, synclinal or folded. This intrusion-form has several very important illustrations. The type-mass is the Duluth gabbro in Minnesota, but perhaps the Sudbury intrusion in Ontario illustrates the type even better. The outcrop of the Sudbury sheet is roughly boat-shaped, with a length of 36 miles and a maximum width of 17 miles. The roof of the intrusion is formed of sediments of the Animikie series; the floor is of granite and old metamorphic rocks. The bottom of the "boat" is naturally unknown; it is possible that the mass is funnel-shaped rather than boat-shaped in depth.

Another grand illustration of the lopolith is the Bushveld complex of the Transvaal, which covers 250 miles from east to west and 150 from north to south. All round the margin of this complex intrusive body the sedimentary rocks dip inwards, forming a basin in which the eruptive rocks lie; but the original roof of the complex has been largely eroded away and in part replaced by younger sediments. Such huge intrusions as this seldom conform exactly to any of our simple types. Although it is correct to say that the Bushveld complex rests on a

sedimentary floor, its relation to that floor is a gradually transgressive one, the base of the complex descending to lower and lower horizons from south to north.

The Duluth, the Sudbury and the Bushveld lopoliths all show gravity stratification, the higher horizons being composed of lighter, more siliceous rocks than lower horizons. The lower portion of the Bushveld complex shows a secondary differentiation of a very complicated kind, lighter and heavier layers alternating rapidly and giving rise to a kind of stratification.

From the laccolith and the lopolith, which we know to have sedimentary floors, at least in part, we pass to the consideration of the *stock* and the still more gigantic *batholith*. These are distinguished from other intrusions more by what we do not know than by what we do know of their structure, our knowledge being confined to the upper surface. The batholith and the stock (Prof. Daly has suggested that the latter term should be restricted to intrusions that have an area of less than forty square miles) have an intrusive relation to whatever rocks they invade; their tops are domes, from which wedges, dykes and pipes project into the country rocks. On the flanks of the dome the eruptive rock descends slowly until it passes beyond our range of observation. Of the floor of a batholith, if it has a floor at all, nothing is known. In short, the characters of a batholith are great size, great thickness, irregular shape, and generally discordant (transgressive) relation to the country rock.

The term *pluton* (the complement of *Vulkan* or volcano), due to H. Cloos, may be applied to any deep-seated intrusive body, regardless of its size or shape.

The conception of a batholith as a floorless intrusion has been challenged. W. G. Foye was able to show that some of the supposed granite batholiths of Ontario are really floored intrusions of laccolithic type; and H. Cloos, in a series of brilliant tectonic studies, has shown that other supposed batholiths are in reality thick sheets or cakes which have been intruded laterally, not vertically,

into their present position. Cloos' method of study depends on the interpretation of such structures as foliation, joints, flow-banding, and pegmatite veins in the rock. When viscous magma in the act of crystallizing is subjected to unequal compression, structures are developed which form a permanent record of the distribution of pressure within the mass. The growing crystals tend to arrange themselves with their long axes perpendicular to the direction of greatest pressure, and so give a distinct grain to the rock; and trains of enclosures and streaks of darker or lighter contaminated or differentiated magma assume the same orientation. As solidification advances, shrinkage-cracks are formed which naturally gape in the direction of least pressure and therefore strike in the direction of greatest pressure; these cracks may become filled with pegmatite or vein-quartz. After the last of the fluid has solidified, further cooling leads to the development of open joints, of which the main series are parallel and perpendicular to the grain of the rock; and still later adjustments give rise to shear-planes and gliding-planes. Thus the accurate mapping of the principal structural directions observed in various parts of a large intrusive mass gives a key to the direction and distribution of pressure at the time of intrusion, and so to the manner in which the mass came into place.

The huge intrusions which are called batholiths, whether they really conform to the definition of the type or not, seem in almost all cases to be composed of quartz-rich rocks such as are covered by the name "granite" used in a wide sense. Batholiths of the largest size frequently show one monotonous type of granite, scarcely varying even in texture, over hundreds of square miles. In other cases there is a wide marginal zone of mixed rocks, within which granitic and sedimentary material—the latter highly altered by contact metamorphism—are intermingled in the most complicated fashion. Near such contact-zones the granite may be found to hold unusual minerals such as cordierite, andalusite, sillimanite, garnet

or epidote, and to show a rapid change of composition from normal granite into granodiorite, syenite, pyroxenite and other rocks.

In the case of minor intrusions, the *manner of emplacement* is obvious enough. Dykes have been injected from below, along fissures which either existed beforehand or were opened up in front of the advancing magma as wood splits before a wedge. Sills spread along existing planes of weakness—the bedding-planes between layers of sedimentary rock—and so do laccoliths and phacoliths. Certain geologists have claimed that sills come into position by dissolving and replacing a particular bed, but the chemical evidence is completely opposed to any such contention. That does not mean, however, that it is impossible for a *limited amount* of sediment to be dissolved or incorporated in the advancing magma.

The lopolith or basin-shaped intrusion is harder to explain, yet in a broad sense it seems to have been directed by the structures of the country rocks. It is when we come to the great transgressive intrusions, the stock and the batholith, that the difficulty of understanding the mechanics of the intrusive process is greatest. It has been claimed that batholiths rise by dissolving the solid rock whose place they take. It is true that there is often strong evidence of corrosion and solution of the wall-rocks, but in general the demonstrable amount of assimilation is absurdly out of proportion to the magnitude of the intrusive body. Did the batholith come into being, then, by the magma squeezing aside the rocks whose place it takes? To some extent this is true, but more often the invaded rocks have been abruptly cut across instead of being pushed aside. In that case the only explanation that remains is that great blocks of the country rock were wedged away from the roof of the rising batholith, and that they sank down through the magma, to accumulate—or it may be to be dissolved—at deeper levels beyond our observation. This process has been called “overhand stoping.” It is most

likely that displacement of beds, stoping, and solution have all played a part in making room for the great transgressive intrusions.

In the case of the great granitic plutons, it is held by some that they were generated in place by transformation of sedimentary rocks under the influence of ascending solutions rich in alkalis. This hypothesis gets rid of the mechanical problem of intrusion, but raises chemical problems which can only be solved by piling hypothesis on hypothesis. We shall not discuss the matter here.

One of the most interesting problems in petrology is to find out to what extent a given magma has been affected in composition by dissolving material from its walls. There is need of far more evidence than we possess in this matter; and it is essential that field evidence and mineralogical observations should be confirmed by good and adequate chemical data. In addition to the modifications suffered by the magma itself, at its junctions with other rocks, the effect of the heat of the magma and of magmatic emanations upon the country rock must also be studied.

The variations in mineralogical and chemical composition which are shown by many eruptive masses, from one part to another, are specially interesting for the light they throw on the history of the magma. Examples of such variations have been mentioned on earlier pages—they include composite dykes, sheets and laccoliths showing gravity stratification, batholiths with basic marginal facies, and so on. Such phenomena are sometimes described as if they were the result of a mysterious process called "magmatic differentiation." To say that a peculiar rock-facies is "due to magmatic differentiation" is to say that a thing is different because it is different, and explains nothing. One might as well say that the relative positions of London and Paris are "due to geographical distribution." Magmatic differentiation, like geographical distribution, is a result, not a process, and it has many possible causes, some of which have been

hinted at in the foregoing pages and all of which deserve most particular study by the petrologist.

SUGGESTIONS FOR READING.

- R. A. DALY, *Igneous Rocks and the Depths of the Earth*.
Chap. 6, Injected Bodies.
Chap. 7, Subjacent Bodies.
Chap. 8, Extrusive Bodies.
- H. CLOOS, *Das Batholithenproblem* (Berlin, 1923).
- C. S. HURLBUT and D. T. GRIGGS, *Igneous Rocks of the Highwood Mts., Montana*. Bulletin of the Geological Society of America, vol. 50, 1939, pp. 1045-1056.
- J. D. BARKSDALE, *The Shonkin Sag Laccolith*. American Journal of Science, XXXIII., 1937, p. 321.
- J. GEIKIE, *Structural and Field Geology* (1940), chaps. 13 and 14.

CHAPTER III.

THE COMPOSITION OF ERUPTIVE ROCKS.

It is rather surprising to find that in spite of the great difference in appearance between one rock and another, the same minerals occur in nearly all. Quartz, feldspar, mica, augite, hornblende, olivine: every known eruptive rock contains one or more of these, and most contain two or more. Add tourmaline, garnet, magnetite, ilmenite, sphene and apatite, and you have all the significant ingredients of ninety-nine per cent. of the eruptive rocks. Add six more: nepheline, leucite, zircon, epidote, spinel, and pyrite: and you have all that you are likely to come across even in a wide experience. This makes the study of eruptive rocks seem very simple, but the apparent simplicity is neutralized by the complex constitution of some of the above silicates, which have the character of *solid solutions* with a wide range of chemical composition. The nature of solid solution may be illustrated most simply by reference to simple salts which are soluble in water.

The sulphates of magnesium, zinc, nickel and cobalt are isomorphous, that is, they have very similar chemical properties and in addition they form crystals of nearly identical habit and angles, each holding seven molecules of water of crystallization. If a crystal of one of these salts—say magnesium sulphate—is introduced into a saturated solution of another—say the cobalt salt—it will grow as freely as if it were in its own mother-liquor, but the new layers will be formed of pink cobalt sulphate. If the crystal is removed after a time and placed in a saturated solution of the nickel salt, the pink layer will be succeeded by a layer of green nickel sulphate, and so on.

But if all four sulphates are present in one solution, then the crystals which separate out on cooling are homogeneous, and each contains all four sulphates almost in the proportions in which they are present in the liquid. It is thus possible, by varying the composition of the solution, to prepare crystals which shall contain any desired proportions of zinc, magnesium, nickel and cobalt; and if one were given such a crystal, it would be impossible, without chemical analysis, to ascertain its precise composition.

Such crystals, whose composition varies with that of their mother-liquor, are solid solutions; and the property of forming solid solutions and layered crystals, or overgrowths, is characteristic of all isomorphous substances. It is a consequence of similarity of ionic radius and of valence, in the mutually replaceable atoms. Among the rock-forming minerals, cases of isomorphism and solid solution are so numerous and important that they have led to the grouping of these minerals into large "natural families," the names of which are usually better known than those of the simple species which make them up. We must now pay some attention to the chemical characters of the principal families of rock-forming minerals.

The Feldspar Family contains four distinct species, in nature, and several series of solid solutions. The species are:—

KAlSi_3O_8 (orthoclase or microcline)

$\text{NaAlSi}_3\text{O}_8$ (albite)

$\text{CaAl}_2\text{Si}_2\text{O}_8$ (anorthite)

$\text{BaAl}_2\text{Si}_2\text{O}_8$ (celsian)

Orthoclase and albite form a series of solid solutions which are called soda-orthoclase or potash-albite, according to which component preponderates. Practically all the "orthoclase" which we identify in rocks is soda-orthoclase, containing an average amount of fifteen per cent. of albite, according to H. L. Alling's determina-

tions. Under changed physical conditions, these solid solutions sometimes split up into their components, or "come unmixed," so giving rise to the minute intergrowths of orthoclase and albite which we know as perthite and microperthite. Microcline is a low-temperature form of potash-feldspar, found especially in the more coarse-grained rocks.

Albite and anorthite give a series of solid solutions to which the group-name of "plagioclase" is applied. Oligoclase, andesine, labradorite and bytownite are names given to those sections of the plagioclase series which hold from 10 to 30, 30 to 50, 50 to 70, and 70 to 90 per cent. of anorthite respectively. The crystals of plagioclase in rocks are sometimes homogeneous and sometimes layered, like the magnesium sulphate crystals described above. In the latter case, the cores of the crystals are generally rich in anorthite and the layers are progressively richer in albite towards the outside.

A soda-anorthite, $\text{Na}_2\text{Al}_2\text{Si}_2\text{O}_8$, has been prepared synthetically and named carnegieite. Pure carnegieite has not yet been positively identified in any rock; but certain basalts which have a very low silica content, although they contain no feldspathoids, have been supposed to hold soda-anorthite in solid solution in plagioclase.

Ternary solid solutions, containing orthoclase, albite and anorthite, also occur; indeed the members of the binary series that we have been discussing nearly always hold a little of the third component, but either so little lime is present that the mineral does not differ greatly from soda-orthoclase, or else so little potash that the product is scarcely distinguishable from a binary plagioclase. The composition of any feldspar is conveniently expressed by the use of Or, Ab and An as shorthand symbols for the pure components; thus $\text{Or}_{74}\text{Ab}_{26}$ is a soda-orthoclase and $\text{Ab}_{32}\text{An}_{68}$ is a plagioclase falling in the labradorite range. (The numbers indicate parts by weight, not molecular proportions.)

The Metasilicate Family. This is a convenient sack-name for the two series of minerals known as the *pyroxenes* and the *amphiboles*, which are distinguished mainly by a difference of crystal habit. The pyroxene habit is characterized by a cleavage angle of about 90° , the amphibole habit by an angle of about 55° . The simple pyroxenes and amphiboles are as follows:—

<i>Pyroxene formula.</i>	<i>Pyroxene.</i>	<i>Amphibole.</i>
1. MgSiO_3	Enstatite	Anthophyllite
2. FeSiO_3	—	Grünerite
3. CaSiO_3	Wollastonite	—
4. $\text{CaMg}(\text{SiO}_3)_2$	Diopside	Tremolite
5. $\text{CaFe}(\text{SiO}_3)_2$	Hedenbergite	—
6. $\text{NaAl}(\text{SiO}_3)_2$	Jadeite	Glaucophane
7. $\text{NaFe}(\text{SiO}_3)_2$	Ægirine	Riebeckite

The chemical formula of an amphibole is more complex than that of the corresponding pyroxene, the unit cell containing eight Si atoms, and one atom of Mg or Fe being replaced by two (OH) groups. Thus the formula of anthophyllite is $(\text{OH})_2\text{Mg}_7\text{Si}_8\text{O}_{22}$, and tremolite is $(\text{OH})_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}$.

From these simple species a wide range of solid solutions may be formed. It will simplify matters if we think of them in four groups, as follows:—

Group A. The *ortho-pyroxenes* are solid solutions of 1 and 2, crystallizing in the orthorhombic system. The name *hypersthene* is given to those richer in iron.

Group B. The *clino-pyroxenes* are monoclinic in crystallization. They fall into four series.

- The *diopside* series contains molecules 4 and 5.
- The *augite* series contains some Al_2O_3 and Fe_2O_3 in addition to the above.
- The *pigeonite* series has 1 and 4 as its characteristic members.

- (d) The *soda-diopside* series contains No. 7 along with Nos. 4 and 5, forming what is sometimes called "ægirine-augite."

Group C. *Ortho-amphiboles* are only found in metamorphic rocks.

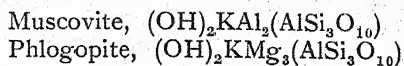
Group D. *Climo-amphiboles* fall into three series.

- (a) The *actinolite* series, consisting of tremolite and its iron-bearing variety, actinolite. These correspond to the diopside series in B, and are found only in metamorphic rocks.
- (b) The *hornblende* series, corresponding to the augite series in B.
- (c) The *soda-amphiboles*, including glaucophane, riebeckite, crocidolite, and a number of ill-defined varieties, such as arfvedsonite, hastingsite, barkevikite and cataphorite, which are intermediate in composition between common hornblende and the true soda-amphiboles.

When one considers all the possibilities in the way of solid solution in this family, it becomes evident that the "augite" and the "hornblende" which the petrographer identifies in his rock sections are far indeed from being minerals of definite composition. The following table illustrates the wide range of composition observed in specimens of augite and hornblende from various eruptive rocks.

	<i>Augite.</i>	<i>Hornblende.</i>
SiO ₂	44.5 to 53.6	38.4 to 54.8
Al ₂ O ₃	2.8 " 9.1	1.5 " 17.5
Fe ₂ O ₃	0.2 " 7.9	nil " 19.1
FeO	1.4 " 15.0	0.9 " 22.2
MgO	10.0 " 17.0	2.5 " 19.5
CaO	15.9 " 23.4	9.5 " 14.3
Na ₂ O	nil " 1.4	nil " 3.1
K ₂ O	nil " 1.1	nil " 2.1
TiO ₂	nil " 4.2	nil " 10.3
H ₂ O	nil	nil " 2.7

The Mica Family contains the following species:—



Biotite is similar to phlogopite but contains much iron, and lepidolite is a lithia-bearing mica. Fluorine is often present, especially in the lithia-micas. The range of composition that is exhibited by rock-forming biotite appears in the following table:—

SiO_2	from	32.0 to 50.9
Al_2O_3		10.9 „ 36.7
Fe_2O_3	trace	„ 24.9
FeO	„	„ 30.3
MgO	„	„ 28.9
Na_2O	„	„ 2.7
K_2O	6.5	„ 10.2
Li_2O	trace	„ 5.4
H_2O	„	„ 6.2
TiO_2	„	„ 4.7
F	„	„ 7.6

The Tourmaline Family. Many elaborate formulæ have been proposed to express the constitution of this complex family. According to Bragg, the unit cell contains about 150 atoms, of which 93 are oxygen. The proportion of aluminium is always high. In common black tourmaline the other metals are chiefly magnesium and iron, and all tourmaline contains about 10 per cent of B_2O_3 . Fluorine is a minor component of most varieties, and a variable amount of water or hydroxyl is always present. The composition of common tourmaline is consequently quite as variable as that of hornblende or biotite, as the following analytical data will show:—

SiO_2	34.6 to 41.1
B_2O_3	9 „ 11
Al_2O_3	25.2 „ 44.0
Fe_2O_3	trace „ 6.6
Cr_2O_3	„ „ 10.8
FeO	„ „ 14.4
MgO	„ „ 14.9
CaO	„ „ 5.1
Na_2O	„ „ 3.5
K_2O	„ „ 2.1
Li_2O	„ „ 1.7
H_2O	„ „ 4.6
F	„ „ 1.1

The Olivine Family. So far as concerns eruptive rocks, this is a group of orthosilicates of magnesia and iron.

The simple olivines are forsterite, Mg_2SiO_4 and fayalite, Fe_2SiO_4 . The common olivine of gabbros and basalts is a solid solution of forsterite and fayalite, the observed range of composition being roughly as follows :—

SiO_2	36 to 42%
TiO_2	nil „ 6
FeO	5 „ 49
MgO	16 „ 51
CaO	nil „ 1.4
MnO	nil „ 1.5

The Nepheline Family. In addition to nepheline itself, we may place in this family the sodalite group of minerals and cancrinite, all of which are most simply regarded as addition products of nepheline. The empirical formula for nepheline is NaAlSiO_4 ; and the formulæ of sodalite, haüyne, nosean and cancrinite can be written in an easily remembered form as 6Nepheline + Na_2Cl_2 , 6Nepheline + CaSO_4 , 6Nepheline + Na_2SO_4 , and 6Nepheline + NaHCO_3 respectively.

Pure kaliophilite or potash-nepheline is a rare mineral, but most natural nepheline is a solid solution of kaliophilite in nepheline, having roughly five times as much soda as potash. The following range of composition has been observed in nepheline:—

SiO ₂	41.9 to 45.1
Al ₂ O ₃	29.4 „ 34.5
Na ₂ O	14.4 „ 18.6
K ₂ O	.9 „ 7.1
CaO	— „ 2.0 (impurity?)

The members of the nepheline family, together with leucite and analcime, are often called “feldspathoids.”

Leucite and Analcime. The empirical formula of leucite is KAlSi_2O_6 . The formula of analcime is similar to that of leucite, with soda in place of potash, and with water of crystallization added; it is generally written $\text{NaAlSi}_2\text{O}_6 + \text{H}_2\text{O}$. J. Lemberg showed that leucite can be transformed into analcime, or analcime into leucite, by treatment with solutions of soda and potash salts respectively at 180° . In spite of this simple relationship, natural leucite contains very little soda, and natural analcime seldom more than a trace of potash.

The Garnet Family includes a number of isomorphous species which conform to the empirical formula $\text{R}_3\text{X}_2(\text{SiO}_4)_3$, where R stands for magnesium, calcium, ferrous iron or manganese, and X for aluminium, ferric iron, titanium or chromium. Some of the simpler species are as follows:—

Grossularite	$\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$
Pyrope	$\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$
Spessartite	$\text{Mn}_3\text{Al}_2(\text{SiO}_4)_3$
Almandine	$\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$
Melanite (andradite)	$\text{Ca}_3\text{Fe}_2(\text{SiO}_4)_3$

Common garnets are solid solutions of two or three of these species at once. Grossularite is confined to meta-

morphic rocks, but the other species occur scantily in eruptives. Pyrope is found in highly magnesian rocks with a low content of silica; melanite also in rocks of low silica content, especially near contacts with limestone; almandine and spessartite occur in very acid granites and pegmatites. The following range of composition is shown by the garnets of eruptive rocks:—

SiO ₂	from	26.1 to 44.8
Al ₂ O ₃	trace	„ 25.4
Fe ₂ O ₃	„	„ 29.1
FeO	„	„ 33.8
MnO	„	„ 32.2
MgO	„	„ 16.4
CaO	„	„ 32.8
TiO ₂	„	„ 21.3

The Melilite Family. This complex group of solid solutions is not yet fully understood, but it is thought to contain the following simple molecules:—

1. Gehlenite 2 CaO, Al₂O₃, SiO₂
2. Akermanite 2 CaO, MgO, 2 SiO₂
3. Soda-melilite Na₂Si₃O₇

According to Bragg, the general formula is (Ca,Na)₂(Mg,Al,Si)₃O₇. Analyses of melilite show the following range of composition:—

SiO ₂	38.3 to 44.7
Al ₂ O ₃	6.4 „ 12.0
Fe ₂ O ₃	0.5 „ 10.2
FeO	nil „ 3.7
MgO	5.7 „ 8.6
CaO	27.5 „ 35.6
Na ₂ O	1.9 „ 4.7
K ₂ O	.3 „ 1.5

The Epidote Family appears, from its empirical formula, to be closely related to the garnet family. The simple lime-epidote (zoisite) has the formula

$\text{Ca}_2(\text{AlOH})\text{Al}_2(\text{SiO}_4)_3$. Common epidote differs from this only by having part of the aluminium replaced by iron. In allanite, or cerium epidote, aluminium is partly replaced by cerium, lanthanum, and didymium.

The Silica Group. Quartz is the stable form of silica at all temperatures up to 870°Cg. ; above that temperature it transforms into tridymite. Quartz itself exists in two forms which differ slightly in appearance and crystallographic character and have a transformation point at 573° . The high-temperature form, or β -quartz, is the one usually found in eruptive rocks; it crystallizes in simple hexagonal bipyramids. The low-temperature form, α -quartz, occurs in some coarse-grained granites and pegmatites; it is also the common form in quartz veins and drusy cavities, and it is characterized by a strong development of the prism faces, which are capped by positive and negative rhombohedrons. Quartz alone is found in deep-seated rocks, but tridymite is not uncommon in acid lavas. Chalcedony and opal are low-temperature forms of silica liberated during weathering; they are never found in perfectly fresh igneous rocks.

Other Oxides. The commonest of these is magnetite, Fe_3O_4 , or $\text{FeO}, \text{Fe}_2\text{O}_3$. The ferrous iron in this formula is replaceable by magnesium or manganese, and the ferric iron by aluminium or chromium, giving a series of isomorphous compounds which are known collectively as spinel. Ferric iron is also replaceable to a considerable extent by titanium, giving titanomagnetite, which forms a connecting link between pure magnetite and the highly titaniferous ilmenite, FeTiO_3 .

Hematite, Fe_2O_3 , is a scanty constituent of many eruptive rocks, and is perhaps in most cases an alteration product. Corundum, Al_2O_3 , is an uncommon constituent of eruptive rocks; it is found chiefly in quartz-free pegmatites.

Zircon and Zirconsilicates. The principal minerals which carry zirconium, in eruptive rocks, are

Zircon, ZrSiO_4
 Eucolite (eudialyte), $\text{Na}_3\text{Ca}_3(\text{SiO}_4)_3\text{ZrCl}$

Also catapleiite, wöhlerite, rosenbuschite and others. Zircon alone is of common occurrence; it is present in most rocks, but only in minute quantity.

Titanosilicates and Titanates. Many minerals have already been mentioned in which titanous acid replaces silicic acid to a limited extent. The following should be added:—

Sphene, CaSiTiO_5
 Perovskite, CaTiO_3
 Astrophyllite, $\text{Fe}_4\text{Na}_4\text{TiSi}_4\text{O}_{16}$

Sphene is very common in granites, tonalites, syenites and nepheline rocks.

Phosphates. In addition to apatite, $3\text{Ca}_3\text{P}_2\text{O}_8$, CaF_2 , which is found in traces in nearly all eruptive rocks, it appears that xenotime, YPO_4 , is not uncommon in granites and syenites, where it is often mistaken for zircon. Monazite, a phosphate of the cerium group of metals, occurs in some granites.

Sulphides. Iron pyrites, FeS_2 , and pyrrhotite (magnetic pyrites) Fe_3S_4 are common. Other sulphides, such as chalcopyrite, CuFeS_2 , bornite, Cu_5FeS_3 , pentlandite $(\text{Fe}, \text{Ni})\text{S}$, and mispickel, FeAsS , are occasionally identified.

Fluorides and Fluosilicates. Among these are fluorspar, CaF_2 , and topaz, $\text{Al}(\text{AlF}_2)\text{SiO}_4$, both of which are often found in the marginal facies of granite masses and in pegmatites.

THE RELATIVE ABUNDANCE OF VARIOUS MINERALS AND
OXIDES.

By comparing the proportions of the principal minerals in thousands of rocks, F. W. Clarke was able to make the following estimate of the mineralogical composition of the average eruptive rock :—

Feldspars	... ..	59 per cent.
Pyroxenes and amphiboles	... ..	17 „ „
Quartz	... ..	12 „ „
Micas	... ..	4 „ „
All other minerals together...	... ..	8 „ „

We also owe to F. W. Clarke, together with H. S. Washington, a most careful computation of the average chemical composition of eruptive rocks, which is as follows :—

SiO ₂	59.12	TiO ₂	1.050
Al ₂ O ₃	15.34	P ₂ O ₅	.299
CaO	5.08	MnO	.124
Na ₂ O	3.84	CO ₂	.101
FeO	3.80	S	.052
MgO	3.49	Cl	.048
K ₂ O	3.13	ZrO ₂	.039
Fe ₂ O ₃	3.08	F	.030
H ₂ O	1.15	Rest	.227

It is also of interest to observe the maxima and minima of the principal oxides. For this purpose we should exclude from consideration the pegmatites which carry low-temperature quartz and pass over into pure quartz veins, and also all rocks which carry an unusually large proportion of oxides, sulphides, or other non-silicate minerals. Subject to these limitations, we find that silica varies between forty and eighty per cent., the higher value being approached by many granites and the lower one by rocks that are rich in anorthite, olivine, nepheline or melilite. Alumina may be almost zero in olivine-rocks, and it rises to more than thirty per cent. in those rich in anorthite

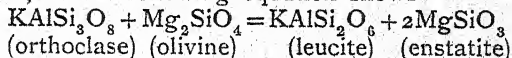
or nepheline. Lime is most abundant in some garnets and in diopside and anorthite; over twenty-five per cent. of lime has been recorded in certain garnet-bearing pyroxenites. On the other hand, the proportion of lime in alkaline granites and in peridotites is almost zero. Magnesia reaches its highest value—nearly fifty per cent.—in peridotites, and sinks almost to nothing in many granites and nepheline rocks. Soda approaches twenty per cent. in rocks that carry much nepheline or sodalite, and dwindles to vanishing point in peridotites. Potash is highest in rocks that contain much leucite, as much as eighteen per cent. having been recorded in an extreme case, and sinks almost to zero in anorthosites and peridotites. Over thirty-five per cent. of ferrous oxide has been found in a peridotite that carried an exceptionally iron-rich variety of olivine; while some granites hold no more than a trace of iron in any form.

The rarer oxides in eruptive rocks are often observed to vary in sympathy with certain of the more abundant ones. For instance, tin dioxide is only found in rocks with a great excess of silica; nickel and chromium oxides in highly magnesian rocks; manganese and vanadium go with much iron; and strontia with lime. Baria, on the other hand, is associated particularly with potash; while richness in soda generally involves an unusual concentration of zirconia, titania and rare earths (ceria, yttria, etc.), as well as manganese, chlorine, fluorine and phosphoric acid. Such observations as these clearly indicate the importance of petrology in the study of ore deposits.

When one has identified all the minerals in a rock, and determined their proportions by the use of a micrometer or otherwise, it is possible from these data to calculate the chemical composition of the rock. The two columns that follow give the composition of the granite of Butte, Montana, as determined (1) by direct analysis (H. N. Stokes), (2) by computation from the minerals present (J. P. Iddings).

	(1)	(2)
SiO ₂	64.34	64.83
Al ₂ O ₃	15.72	16.42
Fe ₂ O ₃	1.62	1.48
FeO	2.94	2.39
MgO	2.17	2.01
CaO	4.24	4.35
Na ₂ O	2.76	2.97
K ₂ O	4.04	4.11
H ₂ O	1.01	.67

The agreement is remarkably good. The converse process of calculating the mineralogical composition of a rock from the results of chemical analysis can seldom be performed with equal certainty, because under different conditions the same group of oxides may combine in various ways, giving different minerals. To take a single case, a mixture of potash, magnesia, alumina and silica may form either orthoclase and olivine or leucite and enstatite, as the following equation shows:—



It is for this reason that the mineralogical rather than the chemical composition of rocks has generally been used as the basis of classification. Given a statement of the mineralogical composition such as is conveyed by the name dolerite, one can form a mental picture of the rock; but from a statement of the oxides present in the rock it is not usually possible to form such a picture.

WORKS OF REFERENCE.

Descriptions of all the rock-forming minerals will be found in the works named at the end of Chapter I.

CHAPTER IV.

THE CLASSIFICATION OF ERUPTIVE ROCKS.

Almost the greatest difficulty that a student meets is what to call a rock when he has finished studying it. The writer, as a student, was once faced with the necessity of choosing between granitite, granodiorite, tonalite, adamellite, banatite, quartz-monzonite, and quartz-diorite, and came after many hours to the conclusion that it didn't matter which name he used since all seven names indicated the same association of minerals and none of them had been defined in quantitative terms. The case was not an unusual one; had the rock contained nepheline the choice of names might have been wider still. The truth is that rock names have been coined in a most haphazard way by workers who have followed no plan or governing principle; and instead of different names indicating different objects, as they do in botany or chemistry, the names overlap in all directions, so that one rock may quite well be covered by half a dozen different names.

The germ of this confusion lies in the nature of the rocks themselves. Granite does not differ from diorite as oak does from ash. Oak is one genus and ash is another, and there are no intermediate forms between them; but granite passes in the field by gradual modification into diorite, and there is no natural boundary at which one can say, here granite ends and diorite begins. So geologists, finding rocks of intermediate composition, have generally taken the easy way of giving them new

names. To such lengths has this practice of coining new names been carried that there are now more than six hundred names in existence for eruptive rocks alone.

The earliest attempt at a systematic classification of rocks was made by Linnaeus in the middle of the 18th century. This great naturalist believed that rocks, as well as animals and plants, group themselves naturally into "genera" and "species" having constant and easily recognizable characters. Although Linnaeus' classification soon fell into disuse, concurrently with the advance of mineralogical chemistry, the concept of "rock species" survived and persisted all through the 19th century. Even to-day, petrographers have not entirely outgrown the tendency to name rocks in accordance with old-fashioned ideas of what constitutes a "species" or "rock type." The history of petrography in the 20th century has been a succession of attempts to break away from these old ideas, and to replace them by chemical and physical concepts or subject them to arithmetical control. Unfortunately none of these attempts has commanded general acceptance, so every petrographer has gone his own way, conferring new names and establishing new "rock types" without regard to any system; or else setting up his own system and inventing new names to go along with it.

For the present, students should try to make themselves familiar with the principal systems of classification that have been widely used, and learn to appreciate the good and the bad features of each. Of the many classifications that have been proposed, *ten* are more or less fully summarised in the following pages. It is not intended to suggest that all of these ten are better than certain others that are not mentioned here. The selection was governed partly by the wish to present a variety of different methods upon which students might exercise their critical powers. Of these methods, all have been used in more less widely known text-books.

Ferdinand Zirkel. In his great *Lehrbuch der Petrographie*, of which the first edition appeared in 1866 and the second (and last) in 1893-4, and in his *Mikroskopische Beschaffenheit der Mineralien und Gesteine* (1873), Zirkel employed and strengthened a foundation that had been laid by Justus Roth, Bernhard von Cotta, and other pioneers of the pre-microscopic period. Zirkel's classification is a mineralogical one in which texture plays only a secondary part. There are seven great mineralogical classes which are defined in clear and unequivocal terms, and within each class there are two divisions which express the degree of crystallization. These divisions are described as (a) evenly granular, (b) porphyritic and glassy. The first group consists mainly of plutonic rocks, the second of dyke-rocks and lavas. Against his own judgment Zirkel perpetuated a subdivision of the second group on the basis of geological age, which was current in Germany in his time but has since been abandoned by everybody. If we cut out this unfortunate feature, then we can show the main divisions of Zirkel's classification in a very simple table (page 39). Besides illustrating Zirkel's system, this table should serve to introduce the reader to such common names as granite, rhyolite, syenite, trachyte, diorite, andesite, gabbro and basalt, which we shall use in this chapter without any further explanation. Within most of the groups shown in the table subdivisions were set up, bringing the number of distinct rock names used in Zirkel's system up to sixty-six.

H. Rosenbusch. In the hands of this inspiring teacher, whose *Mikroskopische Physiographie der Mineralien und Gesteine* went through four editions between 1877 and 1907, the system of Zirkel and Roth became increasingly complicated by the addition of new classes and families, which involved the creation of many new names. The seven mineralogical classes of Zirkel's system became ten, in the case of plutonic rocks, and

ZIRKEL'S CLASSIFICATION, SOMEWHAT SIMPLIFIED.

<i>Mineralogical character.</i>		<i>Chief plutonic type.</i>	<i>Chief volcanic type.</i>
Class I. Rocks with alkali-feldspar and quartz or excess of silica		Granite	Rhyolite
" II. Rocks with alkali-feldspar without quartz or excess of silica, without feldspathoids		Syenite	Trachyte
" III. Rocks with alkali-feldspar without quartz or excess of silica, with feldspathoids		Nepheline-syenite	Phonolite
" IV. Rocks with soda-lime feldspar, with or without quartz, without feldspathoids			
(a) with hornblende or mica, with quartz		Quartz-diorite	Dacite
(b) " " " without quartz		Diorite	Andesite
(c) with pyroxene		Diabase (gabbro)	Pyroxene-andesite
(d) with pyroxene and olivine		Olivine-diabase	Basalt
" V. Rocks with lime-soda feldspar, with feldspathoids		Therolith	Tephrite, etc.
" VI. Rocks without feldspar, with feldspathoids		Ijolite	Nephelinite
" VII. Rocks without either feldspar or feldspathoids		<div style="display: inline-block; vertical-align: middle;"> <div style="display: inline-block; vertical-align: middle;">Olivine-rock</div> <div style="display: inline-block; vertical-align: middle;">Pyroxene-rock</div> </div>	<div style="display: inline-block; vertical-align: middle;">Magma-basalt</div> <div style="display: inline-block; vertical-align: middle;">Augite</div>

NOTE.—In practice, the definition of Class II was not followed strictly, rocks with either a little quartz or a little feldspathoid being admitted to this class.

fourteen in the case of lavas; and in addition Rosenbusch established an entirely new division of *dyke-rocks* which was itself subdivided into three branches. The number of distinct specific names which were included in Zirkel's index in 1893 was 139; Rosenbusch in 1907 listed 304 names. It would not be right to hold Rosenbusch responsible for the creation of all these new names, although many of them are due to him and more to his students; but he held such a dominating position in petrology at the beginning of the century that if he had set his face against the indiscriminating manufacture of new names we should have been spared many of our present troubles. The majority of the new names refer to dyke-rocks, and for the confusion in the nomenclature of that group Rosenbusch is mainly responsible.

It is very difficult to present Rosenbusch's system in a tabular form, for his definitions depend largely on texture and on field-associations and are consequently much more subjective than those of Zirkel. On page 41 Rosenbusch's twenty-four families of plutonic and volcanic rocks have been tabulated, and an attempt has been made to indicate the characteristic mineralogical composition of each. For the dyke-rocks a separate scheme is necessary. These rocks were divided by Rosenbusch into

- (a) a group of porphyries, the members of which have essentially the same composition as the plutonic families;
- (b) a group of aplites and pegmatites, which are richer in light constituents than the plutonic types; and
- (c) a group of lamprophyres, in which the dark constituents predominate over the light ones.

Within groups (b) and (c) especially a host of unnecessary varietal names was created.

Alfred Harker. In his *Petrology for Students*, which is the text-book best known to English students, Harker followed Rosenbusch in a general way but re-

ROSENBUSCH'S CLASSIFICATION (OMITTING DYKE-ROCKS)

[X = essential constituent. X = unessential constituent which may or may not be present.]

THE CLASSIFICATION OF ERUPTIVE ROCKS

41

Mineralogical characteristics					
Quartz	Alkali-feldspar	Plagioclase	Nepheline	Leucite	Light minerals predominate
					Dark minerals predominate
X	X	X			X
X	X	X	X	X	X
	X		X	X	X
X	X	X			
X	X	X			
X	X	X			
	X	X			X
	X	X	X		X
	X	X	X		X
				X	X
			X		X
					X

Plutonic families.

Volcanic families.

1. Granite	1. Quartz trachyte
2 Syenite	2. Trachyte
3. Nepheline and leucite-syenite	3. Phonolite
4. Diorite	4. Dacite
	5. Andesite
5. Gabbro and norite	6. Basalt and diabase
	7. Picrite
6. Essexite	8. Trachydolerite
7. Shonkinite and theralite	9. Tephrite and basanite
8. Missourite	10. Leucite and leucite-basalt
9. Ijolite	11. Nephelinite and nepheline-basalt
	12. Limburgite and augite
10. Peridotite and pyroxenite	13. Melilitite basalt
	14. Lamprophyric lavas

tained a sense of proportion which enabled him to distinguish between rocks of continent-building importance and others which are mere mineralogical curiosities. The deep-seated rocks are divided into six groups, as follows :—

- (1) Granites.
- (2) Syenites and monzonites.
- (3) Nepheline-syenites (including ijolites, theralites and other rare feldspathoidal types).
- (4) Diorites.
- (5) Gabbros, norites and pyroxenites.
- (6) Peridotites and serpentines.

The names have the same meaning as in Rosenbusch's system. Harker's treatment of the dyke-rocks is simpler than that of Rosenbusch but follows similar lines. The volcanic rocks fall also into six groups :—

- (1) Rhyolites.
- (2) Trachytes (including some that contain nepheline or sodalite).
- (3) Phonolites and leucitophyres.
- (4) Andesites (including dacites or quartz-andesites).
- (5) Basalts.
- (6) Leucite, nepheline and melilite-bearing lavas.

Harker used or mentioned just over a hundred distinct rock names in the 5th edition of his book.

F. H. Hatch. Hatch's *Text-Book of Petrology* has gone through many editions since it was first published in 1891. In 1926, **A. K. Wells** appeared as joint author. In classifying rocks according to the percentage of silica that they contain, Hatch uses a method that was first proposed by Kjerulf in 1857. The arbitrarily chosen limits of 66 per cent. and 52 per cent. of silica are used to separate an *acid* group of rocks from an *intermediate* group and a *basic* group. In addition, all rocks that hold little or no feldspar are termed *ultra-basic* without regard to their content of silica, although this may actually be as great as sixty per cent. Rocks are further subdivided

into three series characterized by the kind of feldspar present; an *alkali* series characterized by predominant alkali-feldspar or feldspathoid; a *monzonite* series in which more than a third but less than two-thirds of the feldspar is plagioclase; and a *calc-alkali* series in which plagioclase is the predominating feldspar. The alkali series is further subdivided according to the presence or absence of feldspathoids. In his treatment of dyke-rocks Hatch follows Rosenbusch, keeping the silica percentage in the background and even abandoning it at times.

Owing perhaps to the use of the numbers 66 and 52, Hatch's system gives an appearance of precision which is deceptive. The boundaries between acid, intermediate and basic rocks can only be precise if actual determinations of silica are made. This is a tedious and delicate piece of chemical analysis, and there is always a temptation to shirk it and to guess the silica-percentage from the quantity of quartz and feldspar seen in the rock. But then no claim to precision can be made. In any case, what significance can be attached to the numbers 66 and 52? They have no meaning in terms of minerals, for quartz may be present in a basic rock and nearly absent from an acid one. An enstatite rock, by definition "ultra-basic," actually holds more silica than many syenites. The silica factor is not even used consistently in the system, for it is abandoned in dealing with peridotites, perknites and lamprophyres.

A hundred and twenty distinct rock names are used in the text of Hatch's book (1926 edition).

J. P. Iddings. The qualitative mineralogical classification used by Iddings in his *Igneous Rocks* (vol. 1, 1909; vol. 2, 1913) may be described as a last attempt, made by one who had already lost faith in qualitative petrography, to strengthen the Zirkel-Rosenbusch framework and to force all the new rock names into definite pigeon-holes. In his treatment Iddings showed more leaning towards Zirkel's method, which makes the

mineralogical composition of a rock the essential factor in its classification, than towards that of Rosenbusch, with its emphasis on textural differences. Iddings rejected Rosenbusch's division of dyke-rocks and followed Zirkel in recognizing only granular (phanerocrystalline) and dense (aphanitic) rocks; at the same time he introduced a new factor by separating rocks with small amounts of ferro-magnesian minerals from those with large amounts of such minerals. This is a sound move, but the two divisions are only defined by the use of those vaguest of adverbs, little and much.

Iddings began by erecting five classes which were based on the dominance of (I) quartz, (II) quartz and feldspar, (III) feldspar, (IV) feldspar and feldspathoid, (V) feldspathoid. These classes were then subdivided according to the character of the feldspar, giving four groups which were defined as follows:—

- A, alkali-feldspar makes up more than five-eighths of total feldspar;
- B, alkali-feldspar between five-eighths and three-eighths of total feldspar;
- C, alkali-feldspar less than three-eighths of total feldspar;
- D, rock composed almost entirely of dark minerals.

Further subdivision is effected according to the presence of small or large amounts of ferromagnesian minerals, and again according to the phanerocrystalline or aphanitic texture.

Iddings was one of the authors of the Norm system (to be described next) and in his book he used both systems side by side, supplementing the mineralogical descriptions of rocks by chemical analyses and the norms calculated from them. By thus insisting on the importance and demonstrating the value of accurate rock analyses, Iddings performed a lasting service to petrology; but even by using two classifications at once he could not cure the disease that afflicts the science. In his two volumes he used over 270 distinct rock names of

the older type, in addition to a great number of new names peculiar to the Norm system.

Whitman Cross, J. P. Iddings, L. V. Pirsson and H. S. Washington. Dissatisfied with the ambiguities of qualitative petrography, these four distinguished American workers set themselves the task of introducing methods of precision into the science. Their proposals were embodied in a volume called *The Quantitative Classification of Igneous Rocks* which appeared in 1903; and were repeated (with some small changes which experience had shown to be necessary) in Iddings' *Igneous Rocks*. For the purpose of this classification a complete chemical analysis is required in every case. The actual mineralogical composition or "mode" of the rock is set aside in favour of a possible composition called the "norm," which is obtained by calculation from the analytical data. The steps in the calculation are too many to be given here, but the result is to express the composition of the rock in terms of the following simple mineral molecules:—

<i>Siliceous-aluminous (salic)</i>	<i>Ferro-magnesian (femic)</i>
<i>minerals.</i>	<i>minerals.</i>
Quartz	Acmite
Orthoclase	Diopside
Albite	Wollastonite
Anorthite	Hypersthene
Leucite	Olivine
Nepheline	Akermanite
Kaliophilite	Magnetite
Zircon	Hematite
Corundum	Ilmenite
Sodium chloride	Sphene
Sodium sulphate	Apatite, etc.

The norm of a rock is hardly ever identical with its mode, for it will be seen that complex minerals such as augite, hornblende and biotite, which are of very common occurrence in rocks, are replaced in the norm by simpler

molecules like diopside, wollastonite and hypersthene. For most rocks, however, the norm reproduces fairly closely the main characters of the mode. Since it is clear that none of the existing mineralogical names could be fitted to this system, a complete new set of names was supplied by the authors of the system.

The norm classification has had to face the criticism that it is a classification of analyses, not a classification of rocks. It is true that as regards holocrystalline rocks it is a very imperfect classification, ignoring prominent characters and emphasizing some that are trivial or obscure; but it has the advantage over all other systems that crypto-crystalline and glassy rocks can be classified just as easily as coarse-grained ones, and furthermore that glassy rocks fall into the same divisions as their crystalline equivalents.

Nobody now uses the Norm classification by itself, but most petrographers make a practice of calculating the norm of any rock that they analyze and giving the normative name or symbol in addition to the mineralogical name of the rock. With this information one can turn to H. S. Washington's great volume of *Chemical Analyses of Igneous Rocks* and quickly trace other rocks of similar chemical character to the one under examination. This work—a rich mine of information on the chemistry of igneous rocks—is perhaps the greatest boon conferred on petrologists by the Norm system of classification.

Paul Niggli. This system was introduced in *Gesteins- und Mineralprovinzen* (1923) and extended in 1936 (*Schweizerische Mineralogische und Petrographische Mitteilungen*, vol. 16, p. 335). Niggli sought, as A. Osann had done twenty years earlier, to impart precision to the Rosenbusch classification by means of chemical analysis.

Having secured a complete chemical analysis of the rock under consideration, one begins by converting the

percentages of the various oxides into molecular proportions, which are multiplied by 1,000 to get rid of decimal points. Then, the Fe_2O_3 having been doubled and added on to FeO , the molecular numbers of $[\text{Al}_2\text{O}_3 + \text{Cr}_2\text{O}_3 + \text{Ce}_2\text{O}_3]$, $[\text{FeO} + \text{MnO} + \text{MgO}]$, $[\text{CaO} + \text{BaO} + \text{SrO}]$ and $[\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{Li}_2\text{O}]$ are recalculated to 100 and indicated by the symbols *al*, *fm*, *c*, and *alk* respectively. The molecular numbers of SiO_2 and the remaining oxides are reduced in the same proportion as Al_2O_3 to *al*. The symbol *k* stands for the proportion of K_2O in *alk*, and *mg* for that of MgO in *fm*. Finally, the value *qs* is got by subtracting from *si* the quantity of silica necessary to convert all the *alk* into feldspars, the *c* into anorthite and wollastonite, and the *fm* into metasilicates of the metals concerned. If *qs* is strongly positive it indicates the presence of quartz in the rock; if strongly negative, olivine or a feldspathoid is indicated; but a small *qs* value on either side of zero has no definite mineralogical significance.

By means of these factors, Niggli erected at first 12 "magma-groups" (later increased to 43) and 65 "magma-types" (later increased to 183). Each magma-type is defined by an average composition, chosen on the principle that "certain abundant types must stand more or less in the centre of each field." We are not told what principle governed the selection of the rock which thus became the pattern of each magma-type. It cannot have been relative abundance, because many rare rocks such as pianaarite and rockallite have given their names to magma-types. Two other rocks, ijolite and melteigite, are not only rare but they contain exactly the same minerals and occur under identical geological conditions, yet each of them has become the pattern of a separate magma-type. The very term "magma-type" is unfortunate since the rocks just named probably did not exist as magmas at all, but acquired their peculiar characters by reacting with limestone during the process of consolidation.

Since the Niggli system demands a complete rock analysis, one tends to compare it with the norm system. To do this, it is only necessary to take any rock analysis and compute both the norm and the Niggli symbol. An olivine-basalt from East Africa has the following norm:—

orthoclase	10.01	diopside	7.58
albite	28.82	olivine	8.08
anorthite	27.52	magnetite	4.41
nepheline	3.69	ilmenite	4.56
		apatite	3.25

The Niggli symbol computed from the same analysis is

<i>si</i>	<i>al</i>	<i>fm</i>	<i>c</i>	<i>alk</i>	<i>k</i>	<i>mg</i>
119	28	33	25	13	.21	.36

Which set of data is more informative?

Professor Niggli is also the author of a quantitative mineralogical classification of rocks, based upon an earlier one by A. Johannsen which we shall take up next.

A. Johannsen. A qualitative mineralogical classification fails to satisfy some; a quantitative chemical classification does violence to the ideas of others. In Johannsen's *Quantitative Mineralogical Classification of Igneous Rocks* (1917-1922), classes, orders, families and subfamilies are established on purely arithmetical lines, on the basis of the minerals actually present in the rock. The *class* is determined by the proportion of light-coloured minerals (quartz, feldspar, feldspathoids, pale mica, corundum) in the rock, the boundary lines being set at 95, 50 and 5 per cent. The *order*, in the first three classes, depends upon the proportion of anorthite in the plagioclase, the boundaries being set again at 5, 50 and 95 per cent. In class four the order is determined by the proportion of iron ores (magnetite, ilmenite, pyrite, chromite, etc.) with the same limits as before. The *family*, in the first three classes, depends on the ratio of quartz to feldspar or feldspar to feldspathoid, giving 32 families in each order; in class four there are 13 families

in each order, based on the relations between olivine, pyroxene, amphibole and biotite.

Plutonic rocks, dyke rocks and lavas all fall in the same compartments. In the case of glassy rocks the composition must be deduced from the results of chemical analysis, but no rules are laid down for the calculation, although the result must depend on the method followed.

With 4 classes, 16 orders, and no less than 364 families, a large number of new names must be called for, because Johannsen says that "there are undoubtedly many rocks in most of the families." Some new names have been constructed by combining familiar names and adding prefixes, but it seems doubtful whether names like leuco-calcicase-syenogabbro and melamonzonalite convey a very definite meaning to anybody or help to clarify thought. And are the really significant differences between one rock and another so numerous as to justify 364 families?

S. J. Shand. The present writer has tried since 1913 to indicate certain simple lines along which the mineralogical method of classifying rocks may be strengthened so as to give at once precision and chemical significance to the various groups. The complete scheme appeared in *Eruptive Rocks* (1927). It is based primarily on the recognition of certain chemical incompatibilities among the rock-forming minerals. Most of these were recognized by Zirkel and used to define the main groups of his system, but in the hands of Zirkel's successors these natural dividing lines have been increasingly ignored until at the present day they are transgressed without a thought by most petrographers.

All rock-forming minerals may be classed as stable or unstable in the presence of free silica within the ordinary range of magmatic temperature. The former may be said to be *saturated*, the latter *unsaturated* with silica. The principal minerals of each type are named below.

Saturated. All feldspars, pyroxenes, amphiboles and micas; tourmaline, fayalite (iron olivine), almandine

and spessartite garnets, sphene, topaz, magnetite, ilmenite, apatite, zircon.

Unsaturated. Leucite, nepheline, the sodalite group, cancrinite, analcime, common olivine, melilite, melanite and pyrope garnets, perovskite, corundum, calcite.

This grouping of the rock-forming minerals leads naturally to the following classification of eruptive rocks :—

Class I. *Oversaturated rocks*, containing free silica in the form of quartz, tridymite or silica-glass, together with any of the saturated minerals.

Class II. *Saturated rocks*, properly containing neither free silica nor any unsaturated mineral.

Class III. *Undersaturated rocks*, consisting partly or wholly of unsaturated minerals, without free silica.

This class may be subdivided into

(a) a non-feldspathoidal division;

(b) a feldspathoidal division.

In this classification the four major divisions are separated by natural boundary lines which have a definite meaning in terms of the chemistry of the magma, and in each group certain minerals are possible constituents and certain others are totally excluded.

The relation between alumina and soda, potash, and lime affords another significant basis for classification. This relation expresses itself chiefly in the nature of the dark minerals, and gives rise to four types or facies of rocks.

(I) *Peraluminous type*. In these rocks the molecular proportion of alumina exceeds the molecular proportions of soda, potash and lime combined. The excess of alumina goes into muscovite, biotite, corundum, tourmaline, topaz, or an aluminous garnet (almandine or spessartite).

(II) *Metaluminous type*. The proportion of alumina exceeds that of soda and potash combined, but is generally less than that of soda, potash, and lime combined. Nevertheless, some of the alumina

enters the dark minerals, forming either a moderately aluminous mineral such as hornblende, epidote, or melilite, or else an association of an aluminous with a non-aluminous mineral, such as pyroxene and biotite or olivine and hornblende.

- (III) *Subaluminous type*. There is little or no excess of alumina over that required to form feldspars and feldspathoids. The dark silicates are olivine and ortho-pyroxene, which are strictly non-aluminous, and diopside and augite, in which a small proportion of silicon atoms may be replaced by aluminium atoms.
- (IV) *Peralkaline type*. The molecular proportion of alumina is less than that of soda and potash combined. The characteristic dark minerals are the soda-pyroxenes and soda-amphiboles, eudialyte, and other soda-rich species.

This method of classification brings all the dark silicates into four large groups, within each of which the characteristic minerals have more in common, as regards both chemical composition and conditions of formation, than they have with the minerals of any other group. Thus the peraluminous minerals as a whole are characteristic of highly siliceous plutonic rocks and pegmatites formed at very low temperature; the metaluminous group contains minerals that are formed at relatively low temperature, in presence of water; the minerals of the subaluminous group can all be formed by dry fusion (high temperature minerals); and peralkaline minerals are characteristic of highly sodic rocks.

So far the method of classification has been a chemical one, but the divisions have not been established upon arithmetical lines, as in other chemical systems. They depend instead upon the excess or deficiency of one component as regards another, for it is this, and not the absolute number of molecules, that determines what mineral phases shall appear in the system. Consequently every group set up by the application of these principles has a

real chemical significance in a sense that is true of no other classification; and since in each group certain minerals are possible and certain others impossible, the system has also a definite mineralogical significance to a higher degree than any other classification. And these results are secured without the use of any appliance but the microscope.

The next factor in the writer's classification is a textural one, expressive of the physical conditions under which crystallization took place. Only two divisions are recognized, one of well-crystallized (eucrystalline) rocks and one of relatively or actually ill-crystallized (dyscrystalline) rocks. These correspond to the two divisions of Zirkel and Iddings. The line of separation cannot be drawn very sharply, but it is conveniently placed at the limit of unaided vision. A rock in which the principal minerals cannot be seen as separate grains by the unaided eye is dyscrystalline. A porphyritic rock must be judged by its groundmass.

The remaining factors in the classification have only an arithmetical basis. There is first the proportion of light to heavy minerals, that is, those with density less or greater than 2.8. Light minerals (which are light in colour as well as in weight) are quartz, tridymite, feldspars, feldspathoids and calcite. All other rock-forming minerals are denser than 2.8, and most of them are dark in colour. The ratio of light to heavy minerals is therefore almost the same thing as the ratio of light to dark minerals, and it may be called the colour ratio or colour index. Limits are placed at 30, 60 and 90 per cent. by volume of heavy minerals, and the corresponding rocks are described as leucocratic, mesotype, melanocratic and hypermelanic respectively.

Lastly, some means had to be found of expressing the composition of the feldspar in rocks. Not only does feldspar make up some sixty per cent. of eruptive rocks as a whole, but rock names have been defined in terms of feldspar for nearly a hundred years. If one gives up this

practice, then all existing rock names must be abandoned. It seems better to recognize the custom and to take steps to regulate it than to make a radical change which is not unconditionally necessary. The method adopted by the writer is quantitative and depends on the ratio of orthoclase to albite and anorthite. These names stand here for the pure substances KAlSi_3O_8 , $\text{NaAlSi}_3\text{O}_8$ and $\text{CaAl}_2\text{Si}_2\text{O}_8$ which are components of all ordinary feldspar. Four divisions are established in the following way:—

$$\begin{array}{ll} \text{I} & \text{Or} > \text{An} \quad \left\{ \begin{array}{l} \text{(a) Or} > \text{Ab} \\ \text{(b) Ab} > \text{Or} \end{array} \right. \\ \text{II} & \text{An} > \text{Or} \quad \left\{ \begin{array}{l} \text{(a) Ab} > \text{An} \\ \text{(b) An} > \text{Ab} \end{array} \right. \end{array}$$

In favourable cases the necessary observation of the character of the feldspar can be made under the microscope, by methods that are familiar to all students of rocks. In less favourable cases it may be necessary to make an actual determination of soda and potash, either in the feldspar itself or in the groundmass of the rock. *The system proceeds on the assumption that what a petrographer cannot learn by one method he will take steps to find out by the other.* In the case of a rock that is largely or wholly glassy, the composition may be deduced fairly well from the density and the refractive index of the glass; but if these methods do not yield the desired information then the rock must be analyzed, either partly or completely, and its mineralogical character deduced by calculation, following the methods so carefully devised by the authors of the Norm classification.

Only fifty-six rock names have been used in the construction of the writer's system, although it is considered that others may be required in time. The names are not new, but have been chosen from those that are most widely used at the present time. They have been redefined to fit the limits imposed by the system, but in every case the new definition includes the kernel of the old one. Where no suitable name is in existence, none has been

proposed, but sometimes a distinctive prefix or suffix has been added to one of the old names. The names can be changed at any time without affecting the system, for it is an essential feature of this proposal that the names are subordinate to the system, not the system to the names.

In view of the general opposition to new names, the writer offers a set of easily understood symbols which may be added to familiar rock names in order to give them more significance.

X, eucrystalline; D, dyscrystalline.

O, oversaturated (small o if excess silica not more than 10 per cent.).

S, saturated; U, undersaturated, feldspathoidal; V, undersaturated, non-feldspathoidal; W, combines U and V.

p, peraluminous; m, metaluminous; s, subaluminous; k, peralkaline.

α , Or > An, Or > Ab; γ , An > Or, Ab > An.

β , Or > An, Ab > Or; δ , An > Or, An > Ab.

L, leucocratic; M', mesotype; M'', melanocratic; H, hypermelanic. (Instead of these, the value of the colour index may be given.)

Thus the symbol $Xom\alpha L$ means that the rock is eucrystalline, slightly oversaturated, metaluminous, leucocratic, and contains a potassic feldspar. This is a concise summary of the characters of the Plauen syenite, and it is much more informative than the specific name "plauenite" which some petrographers have used.

A. Lacroix. The system of classification followed by this eminent French savant was explained in a *Bulletin du service géologique de l'Indochine*, vol. 20, part 3, 1933. There are actually two systems, one for holocrystalline rocks that have not been chemically analyzed, and another for all rocks which have been analyzed. The necessity for analyzing all cryptocrystalline and glassy rocks is implied.

(a) *For rocks that have not been analyzed.* Lacroix establishes seven categories which, for the greater part, are based on nothing more than the old familiar ratios of quartz to feldspar; feldspar to feldspathoid; potassic to sodic feldspar; sodic plagioclase to calcic plagioclase; nepheline to leucite; dark to light minerals; and degree of crystallization.

(b) *For rocks that have been chemically analyzed.* In this case Lacroix uses a set of symbols (parameters) based on the arithmetical ratios of certain normative minerals and oxides, thus:—

p is the colour index, with limits at $7/1$, $5/3$, $3/5$, $1/7$.

q is the ratio of quartz to feldspar or feldspar to feldspathoid.

r is the ratio of salic alkalis to salic lime.

s is the ratio of salic K_2O to salic Na_2O .

h is the ratio of pyroxene plus olivine to iron ore.

k is the ratio of pyroxene to olivine.

l is the ratio of MgO plus FeO to ferric CaO .

m is the ratio of MgO to FeO .

These are the same ratios that are used in the subdivisions of the Norm system, and comparison with that system is naturally invited.

Summary. In this chapter we have described ten more or less distinct methods of classifying eruptive rocks. These methods may themselves be classified as follows:—

I. Qualitative methods.

(a) Based essentially on mineralogical composition—

Zirkel.

(b) Based largely on texture and geological association in addition to mineralogical composition—

Rosenbusch; Harker.

II. Partly quantitative systems based on mineralogy and texture—**Iddings; Hatch.**

III. Quantitative mineralogical system formed on a purely arithmetical basis—**Johannsen.**

- IV. Quantitative mineralogical system founded on relative excess or deficiency of principal molecules, only the subdivisions being arithmetical—**Shand**.
- V. Quantitative chemical system, modified by other considerations—**Niggli**.
- VI. Quantitative chemical systems independent of other considerations—the **Norm** system; **Lacroix**.

SUGGESTIONS FOR READING.

- WHITMAN CROSS, A Review of the Development of Systematic Petrography in the 19th Century. *Journal of Geology*, vol. X., 1902, p. 431. Also in *Quantitative Classification of Igneous Rocks*, 1902.
- S. J. SHAND, (1) *Eruptive Rocks*, 3rd edition, chaps. 13-14; (2) *The Species Concept in Petrology*. *American Journal of Science*, vol. 242, 1944, p. 45.
- A. JOHANNSEN, *Descriptive Petrography of Igneous Rocks*, vol. 1, pp. 51 to 158.

CHAPTER V.

ERUPTIVE ROCKS: THE OVER-SATURATED CLASS.

By oversaturated rocks we mean those that have an excess of silica which crystallizes out either as quartz or rarely as tridymite. Most rocks that hold much quartz have also a good deal of feldspar, and from the earliest days of geology such rocks, when coarse in grain, have been called granite. Fine-grained dyke-rocks and lavas of similar composition to granite have been variously named quartz-porphyry, rhyolite, liparite; and the vitreous ones obsidian and pitchstone.

After the introduction of the microscope into petrology (about 1858 to 1870) it was recognized that both orthoclase and plagioclase feldspars occur in granite, sometimes one and sometimes the other predominating. Zirkel defined granite as a rock in which alkali-feldspar, quartz and a triclinic lime-soda feldspar always take part; adding that as regards size and number of individuals plagioclase is as a rule much behind orthoclase. For rocks in which plagioclase predominates Zirkel used the name quartz-diorite, making them a subdivision of his fourth class (see the table on page 39). Among the quartz-diorites Zirkel mentions a hornblende-rich quartz-mica diorite from the Tonale massif in the Alps, and tells us that G. vom Rath has given this rock the specific name of tonalite. [Zirkel adds the interesting note that Cathrein prefers to regard this rock as a plagioclase-rich hornblende-biotite granite and has rechristened it adamellite. This is an early illustration of how confusion is caused by failure to define rock names precisely, and how

petrologists have tried to escape from it by coining new names, and how they have made matters worse instead of better.]

Rosenbusch defined the granites as plutonic rocks characterized by the combination of quartz and alkali-feldspar, adding that plagioclase is present in by far the most cases. He went on to subdivide the granites into (a) alkali-lime granites and (b) alkali-granites, but the criteria given for distinguishing these from each other are most vague. In spite of their names, the groups are not based on chemical characters, for Rosenbusch says that "if one were to call every alkali-rich granite which is poor in lime and magnesia an alkali-granite, one would separate what nature has put together and offend against the spirit of geology." He tells us that an alkali-granite is only to be recognized by its peculiar suite of dyke rocks, or by its association in the field with foyaites and other more distinctly alkaline types. Such a typically Rosenbuschian pronouncement is rather disconcerting to the student of the meanings of rock names. The quartz-plagioclase rocks are considered by Rosenbusch, as by Zirkel, to be a subdivision of the diorites, and tonalite and granodiorite are both described under this heading.

J. P. Iddings, following other American petrologists who had attacked the same problem, subdivided the over-saturated rocks in the following way:—

Alkalic granites are those in which more than seven-eighths of the total feldspar is alkali-feldspar.

Calcalkalic granites have alkali-feldspar making between seven-eighths and five-eighths of the total feldspar.

Adamellites or quartz-monzonites have alkali-feldspar from five-eighths to a half of the total feldspar.

Granodiorites have plagioclase from a half to five-eighths of the total feldspar.

Quartz-diorites have plagioclase to the extent of more than five-eighths of the total feldspar.

The joint committee on British Petrographic Nomenclature appointed by the Geological Society of London and the Mineralogical Society of Great Britain recommended in 1921 that the name granodiorite should be used for "rocks intermediate between quartz-diorite and granite, in which orthoclase, while present as a notable constituent, is always subordinate in amount to the plagioclase."

Finally, F. H. Hatch (1926) uses adamellite in the sense in which Iddings used granodiorite, and granodiorite in the sense in which Iddings used quartz-diorite.

It must be added that in spite of all these attempts to rationalize the nomenclature of the oversaturated rocks, there are petrologists who continue up to the present day to give the name granite even to rocks in which all the feldspar is plagioclase.

To the present writer it seems that none of the above definitions is wholly satisfactory, since they are all expressed in terms of alkali feldspar and plagioclase. Alkali-feldspar may be either potash-rich or soda-rich; and plagioclase may be rich in soda or rich in lime; so the ratio of alkali-feldspar to plagioclase is meaningless, because albite occurs as an unknown quantity both in the numerator and in the denominator. If the feldspar is described in terms of orthoclase and anorthite then the definitions can be made clear and precise. The following scheme was proposed in 1927:—

OVERSATURATED ROCKS.

Composition of feldspar.		Eucrystalline.	Dyscrystalline.
Or>An	{ (a) Or>Ab	Potash-granite	Potash-rhyolite
	{ (b) Ab>Or	Soda-granite	Soda-rhyolite
An>Or	{ (a) Ab>An	Soda-tonalite	Soda-dacite
	{ (b) An>Ab	Lime tonalite	Lime-dacite

As regards the *nature of the dark minerals*, Zirkel made the following subdivisions of the granitic rocks :—

- (1) Biotite-granite (with or without hornblende),
- (2) Muscovite-granite,
- (3) Two-mica granite,
- (4) Hornblende-granite (with or without accessory biotite),
- (5) Hornblende-biotite granite,
- (6) Tourmaline-granite.

Rosenbusch gave a slightly different grouping, as follows :—

- (1) Granite in a restricted sense, or two-mica granite,
- (2) Granitite or biotite-granite,
- (3) Hornblende-granite,
- (4) Diopside-granite,
- (5) Hypersthene-granite,
- (6) Tourmaline-granite,

with further subdivisions among the alkali-granites according to the presence of ægirine, acmite, riebeckite, arfvedsonite, etc.

This method of treatment is aimless; it is an enumeration of varieties rather than a logical classification of them. It was shown in Chapter IV (page 50) that a more significant grouping of the dark silicates in rocks can be effected by considering the relation between the molecules of alumina and those of soda, potash and lime in these minerals. Four types were there set up, which were described as peraluminous, metaluminous, subaluminous and peralkaline. We shall make use of these terms when we come to discuss the principal varieties of the over-saturated rocks.

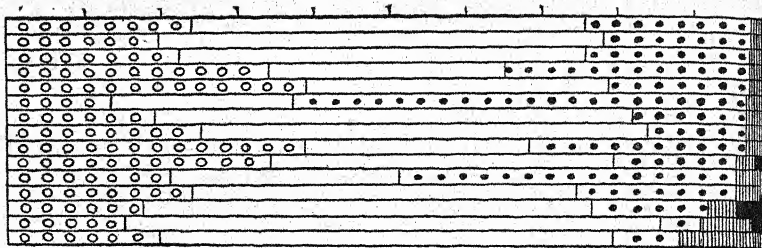
GEOLOGICAL OCCURRENCE.

Granite, granodiorite and tonalite occur typically in batholiths of the largest size. The surface area of the Vermilion batholith in Minnesota is about three thousand square miles, and that of the Boulder batholith in Montana

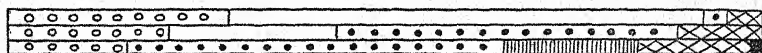
about two thousand. The largest batholith in the Appalachian mountains measures three hundred and fifty miles by fifty, and similar figures are given for the Coast Range batholiths of Alaska and British Columbia. The granite mass of the Wicklow hills in Ireland, with an area of only six hundred square miles, is quite a minor affair.

It is only in a loose sense that we can say that these great intrusions are composed of granite, for actually many varieties of rock are present, from true granite to granodiorite and tonalite and often to diorite and gabbro as well. Very often the core of the mass is normal granite, with less siliceous and more calcic types surrounding it. A graphic picture of the variation in the Vermilion batholith, by F. F. Grout, is reproduced on the next page.

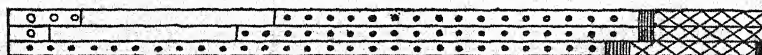
The margin of a granite batholith is sometimes quite sharp, so that one can almost lay a knife-blade along the contact between granite and country-rock; but in other cases the intrusive mass is bounded by an exceedingly ill-defined zone of mixed rocks. In crossing such a zone one may pass from a pale granite to a darker granite that holds streaks and bands of half-incorporated sediment; from this to a belt where the rock is crowded with larger and smaller enclosures of the country rocks; then to a belt where the highly altered country rocks are cut up by a network of granite and pegmatite veins, which die out as one goes further and further away from the granite. The streaky or banded rocks which result from such intermingling are known in general as *gneiss*, and various degrees of contamination of the granitic magma may be expressed by the use of terms such as gneissose granite and granite-gneiss for those parts in which granitic material predominates, and injection-gneiss or migmatite for those in which foreign matter plays a large part. Many of the oldest and largest granitic intrusions in all parts of the world have this gneissic character in part. The Idaho batholith covers some 16,000 square miles, but the greater part of it is injection-gneiss and migmatite.



BIOTITE-GRANITES AND GRANODIORITES



HORNBLLENDE-GRANITES AND GRANODIORITES



SYENITES AND DIORITES



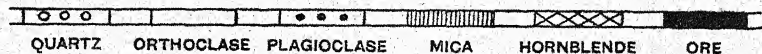
SHONKINITES AND SODA-GABBROS



HORNBLLENBITES



ORE-ROCKS



QUARTZ ORTHOCLASE PLAGIOCLASE MICA HORNBLLENDE ORE

Diagram showing the composition of various rocks of the Vermilion granite batholith. Each horizontal bar represents the composition of one rock. The biotite granites and granodiorites make up nine-tenths of the whole. After F. F. Grout, with slight changes.

It is still an open question whether granitic magma can *dissolve* more than a trifling quantity of foreign rock, but it is certain that a considerable quantity of foreign sedimentary material can be incorporated and recrystallized in granitic magma. Wherever granite is seen to have a streaky character, with alternating lighter and darker folia or bands, then incorporation of foreign rock is to be suspected, and unusual minerals such as cordierite, sillimanite and garnet may be looked for.

It may be thought that as granite, granodiorite and tonalite are quite the most abundant of plutonic rocks, so lavas of similar composition must predominate among the effusive rocks. It is not so. Rhyolite and dacite are common lavas, but not so common as basalt and olivine-basalt. Prof. R. A. Daly has shown that of the total area occupied by plutonic rocks in the United States of America, granite and other oversaturated rocks make up about ninety per cent.; whereas of the areas occupied by effusive rocks, acid lavas only account for some twenty-three per cent. There are no great fields of purely acid lavas to compare with the basalt plateau of the Deccan, or the Columbia River basalts. In the rhyolite fields of Hungary and Iceland, and in the volcanic region west of Great Salt Lake, rhyolites and dacites have an enormous development, but they are associated with basalts and other lavas which may exceed the rhyolites in bulk.

MINERALOGY AND TEXTURE.

The proportion of quartz in an average granite is between twenty and forty per cent. There is no upper limit, for very acid granite may pass over into veins and bodies of pure quartz. The lower limit is naturally zero, but there are practical advantages about establishing an arbitrary boundary at *ten per cent.* of quartz or free silica. When quartz is present in very small quantity it is difficult to recognize, for it forms thin films between the feldspar crystals which may escape notice. Besides this,

many of the most familiar rocks which have been called syenite and diorite actually carry five or ten per cent. of quartz. This is true of the Plauen syenite, which has always been regarded as the typical example of its kind. We may therefore make a small sacrifice of logic for practical ends, and place the lower boundary of the oversaturated class at ten per cent. of quartz or excess silica.

In deep-seated rocks the quartz appears in glassy grains which are interstitial to the larger feldspar crystals. It is always one of the last minerals to crystallize, in such rocks, and owing to the interference of the crystals with one another the quartz grains seldom show good crystal faces. A minority of the crystals, however, have the form of hexagonal bipyramids. These are often enclosed in the outer zones of the feldspar crystals, showing that the crystallization of quartz began before that of feldspar was finished. In many coarse pegmatites or "giant granites," and in the groundmass of some fine-grained dyke-granites and lavas, quartz and feldspar are closely intergrown; forming what is called "graphic granite," when it is coarse, and "micropegmatite" when it is on a minute scale. The quartz in these intergrowths is the low-temperature form (α -quartz), with strongly developed prism faces. The bipyramidal crystals represent the high-temperature variety (β -quartz).

In many lavas, on the other hand, quartz is one of the first minerals to crystallize. It is commonly seen in prominent little bipyramids a few millimetres in diameter, lying in a partly or wholly glassy groundmass. The crystals show signs of having been attacked and corroded by the magma after their formation, and in thin section they present hexagonal to rounded outlines, often with embayments of the glassy groundmass. In lavas, too, silica sometimes appears in the form of tridymite instead of quartz; this mineral is only stable above 870° , and it is never found in deep-seated rocks. The little hexagonal

plates of tridymite are mostly seen in vapour cavities, which makes it rather likely that the mineral did not crystallize directly from the liquid magma but was produced by some reaction in which hot gases took part. Prof. Lacroix thought that the tridymite in the lavas of Mont Pelée had been formed by the action of superheated steam upon the glassy base of the rock. If this is so, then tridymite is a product of auto-metamorphism.

The feldspar of the oversaturated rocks may be of any kind from an almost pure potassic orthoclase or microcline, through soda-orthoclase and microperthite to albite, oligoclase or andesine. As the proportion of anorthite in the feldspar increases, quartz becomes less and less abundant, and when anorthite distinctly exceeds albite in the plagioclase there is seldom more than a trace of quartz left. The feldspar may vary widely in composition in different parts of a single intrusive body. The following figures, which relate to the "granite" of the Wicklow Hills in Ireland, were given by Prof. Sollas:—

Croghan Kinshela	...	1	part orthoclase to 25	parts albite		
Rockabill	...	1	"	"	1.2	"
Blackstairs	...	1	"	"	1.1	"
Poultouny	...	1	"	"	1.2	oligoclase
Three Rock Mountain	1	"	"	"	1.2	"
Carnsore	...	1	"	"	1.4	"
Ballinaclesh	...	1	"	"	3.9	"
Aughrim	...	1	"	"	5.3	"
Ballyknockan	...	1	"	"	1.2	andesine
Ballinamuddagh	...	1	"	"	1.6	"
Coolboy	...	1	"	"	3.9	"
Cushbawn	...	1	"	"	5.1	"

When two kinds of feldspar are present in a rock the plagioclase has generally crystallized before the orthoclase, and microcline forms last of all. But this is not an absolute rule, for in the Rapakivi granites of Sweden and Finland crystals of soda-orthoclase have mantles of oligoclase round them; and in some porphyritic granites the

large crystals are orthoclase and the smaller ones in the groundmass are oligoclase.

According to the habit and arrangement of the feldspar crystals we distinguish three principal varieties of texture in granitic rocks.

(1) The crystals are large but often unequal in size, and are closely packed together without definite orientation. Owing to their mutual interference only a few of them are well shaped. This is granitic texture.

(2) The feldspar crystals are more tabular in shape, with a large development of the second pinacoid, and they lie in roughly parallel position in the rock. Mica scales and hornblende prisms show a similar orientation. This is parallel texture.

(3) Some of the feldspars are large and well shaped and they are surrounded by a matrix of smaller feldspars, quartz, etc. This is porphyritic texture. The large crystals are called in German "Einsprenglinge," which we may translate roughly by the English word "insets." (The word "phenocryst" is a Greek barbarism and should be discouraged.)

The texture of oversaturated lavas varies from microcrystalline-porphyritic to cryptocrystalline — that is, so minutely crystalline as to be almost beyond the power of the microscope to resolve—or it may be partly or wholly glassy. In the extreme case of obsidian there is hardly a trace of crystallization, and the entire rock consists of a black glass which becomes transparent and colourless in thin splinters. In very ancient glassy rocks a process of recrystallization often sets in, just as it does in badly annealed commercial glass. This may lead to the growth of isolated spherules which consist of radiating fibres of quartz and feldspar (in commercial glass such spherules are composed of calcium silicate), or it may cause the glass to become cryptocrystalline throughout, with a stony appearance. In acid lava-flows glassy and stony bands often alternate, giving rise to a banded texture. In the commonest type of spherulite the fibres radiate

out from the centre, growth having started at this point; but in other cases the spherulite is hollow, perhaps in consequence of contraction following the rapid growth of the fibres. When there has been great contraction the result is a system of thin, stony shells with open spaces between them. These have been called "lithophysæ" or stone-bubbles. Interesting studies of spherulites and lithophysæ were made by J. P. Iddings at Obsidian Cliff, in the Yellowstone National Park, and by Whitman Cross in Colorado. A coarser type of intergrowth of quartz and feldspar produces micropegmatite.

The heavy minerals of oversaturated rocks include all kinds of mica; common hornblende and the rarer soda-hornblendes (riebeckite, arfvedsonite, etc.); enstatite, diopside, soda-diopside and ægirine; tourmaline and topaz; iron and manganese garnets (almandine and spessartite), occasionally rare titanosilicates and zirconosilicates such as astrophyllite and eudialyte; as well as small quantities of zircon, xenotime, monazite, epidote, fayalite, sphene, magnetite, apatite.

The crystallization of granite appears to have begun with the accessory minerals such as zircon, allanite and apatite, for minute crystals of these minerals are enclosed in biotite scales. On similar grounds the crystallization of biotite must have begun before that of feldspar, for the large feldspar crystals in granite often carry little scales of biotite right to the centre. Muscovite generally follows biotite, and sometimes surrounds and envelops the biotite platelets. The largest and best-shaped of the feldspars were presumably the first to start their growth; they are always orthoclase; and plagioclase, if present, forms smaller crystals. Perthitic intergrowths of orthoclase and albite or oligoclase are common. Quartz began to crystallize before the feldspars had finished their growth, and there may be a stage during which quartz and feldspar crystallized together as micropegmatite; but the last of the quartz is interstitial to everything else.

EUCRYSTALLINE DIVISION.

(*Granite, granodiorite and tonalite.*)

Granite, loosely defined, is a coarse-grained rock in which both quartz and orthoclase are prominent. Granodiorite is a variety of granite in which orthoclase and plagioclase are about equally abundant (such rocks are also called adamellite and quartz-monzonite), and tonalite is a granitic rock in which the feldspar is mainly plagioclase. The more precise definitions of these names, which the present writer favours, were explained on page 59; but the account which follows is not bound up intimately with any special definition.

The commonest type of **Granite** is the *peraluminous* one, in which alumina is present in excess of the sum of the soda, potash and lime molecules. The excess goes typically into muscovite, but if enough magnesia or ferrous oxide is available then biotite may partly or wholly take the place of muscovite. Other highly aluminous minerals that often appear in granites of this type are tourmaline and topaz; these are found especially in marginal facies of granite bosses and in dykes and veins. Tourmaline is a mineral of late formation, and the larger crystals are usually moulded on grains of feldspar and quartz. Some tourmaline is definitely formed at the expense of feldspar and biotite. The growth of little bunches of tourmaline needles on the surfaces of feldspar crystals can often be studied on joint-faces in granite; when this process goes further the greater part of the feldspar may be replaced by a mass of interlocking tourmaline needles. Such a rock is strictly metamorphic, but the change was not brought about by any agent outside of the granite itself; it is a case of auto-metamorphism or self-replacement. Topaz is also a product of auto-metamorphism; good crystals of topaz are sometimes found in drusy cavities in granite. Some granites carry little crystals of an aluminous garnet (almandine or spessartite), especially where contamination of the magma with sedi-

mentary material has taken place, but fine almandines are occasionally found in pegmatites too.

No better examples of peraluminous granite can be mentioned than those of Cornwall. They are muscovite-biotite granites with subordinate tourmaline and topaz. The texture is typically porphyritic, and the proportion of dark minerals ranges from five to twenty per cent. A careful examination of the granite of St. Austell, by W. A. Richardson, has shown that the average composition of the rock is as follows:—

on of the rocks is as follows.							
quartz	...	...	32.6	tourmaline	...	...	1.8
orthoclase	...	...	34.5	topaz	...	...	1.4
plagioclase	...	...	19.2	fluorite	...	...	0.4
muscovite	...	...	4.5	magnetite	...	...	0.3
biotite	}	...	4.7	apatite	...	...	0.3
lithia-mica				cordierite	...	...	0.3
Colour index							(13)

Within this single granite mass, which has an area of 32 square miles, the chief constituents show the following fluctuations:—

quartz, from ...	20 to 48	white micas, from	0 to 15
orthoclase, from	17 to 52	tourmaline, from	0 to 7½
plagioclase, from	9 to 31	topaz, from ...	0 to 7
dark micas, from	0 to 15	Colour index (4 to 22)	

In the *metaluminous* type of granite the following dark minerals are found: biotite together with hornblende or diopside or both of these; hornblende with diopside; or hornblende alone. Exceptionally epidote or fayalite may be found. The pyroxene has crystallized early and it is often mantled with brown or green hornblende. Biotite and hornblende are frequently intergrown, and the larger hornblende crystals may enclose grains of quartz and feldspar. Sphene is a common accessory constituent. In general, plagioclase is more abundant in hornblendic granites than in micaceous ones; and with an increasing content of plagioclase the rock passes into granodiorite and tonalite. An excellent illustration of a body of hornblende-granite, grading into

granodiorite and having marginal facies of sub-acid granite, syenite, diorite, shonkinite and hornblendite is given by the Saganaga granite of Minnesota and Ontario, which has been described by F. F. Grout. The following table gives the composition of various facies of this rock mass.

	Quartz	Ortho- clase	Plagio- clase	Horn- blende	Access- ories
Central granites, 85-90 per cent. of the mass	43	10	42	5	—
	35	12	48	4	1
	26	28	41	5	—
	26	19	49	5	1
	19	23	51	7	—
	22	29	42	5	2
	20	24	49	5	2
	14	31	45	9	1
	30	20	40	10	—
Border granites	21	22	50	5	2
	20	65	10	—	5
	12	20	55	13	—
	18	11	32	27	12
Border syenites and diorites	10	32	40	15	3
	5	25	45	20	5
	—	7	80	8	5
Shonkinites	6	14	26	53	1
	3	8	22	65	2
Hornblendite	—	5	2	93	—

The *subaluminous* type of granite, in which there is little or no excess of alumina over the alkalis, is scarce among really deep-seated granites, though not uncommon in dyke-granites. The characteristic heavy minerals are ortho- and clino-pyroxenes. The hypersthene-granite or "charnockite" of St. Thomas' Mount, Madras, may stand as a representative of the type, although some authorities consider the charnockites to be metamorphic. It is a fine-grained rock in which the feldspar is mainly microcline, with some oligoclase (Ab_5An_1) and three or four per cent. of hypersthene in little colourless grains.

In the hypersthene-granite of Blue Ridge, Virginia, hypersthene and augite are intergrown.

Peralkaline granites hold soda and potash in molecular excess over alumina. Whenever this is the case, potash seems to exercise the stronger claim to combine with alumina and it is always soda that is left in excess. Under these circumstances the excess of soda forms a soda-iron pyroxene (*ægirine*), a soda-iron amphibole (*riebeckite*, *arfvedsonite*), or else uncommon zirconosilicates and titanosilicates such as *eudialyte* and *astrophyllite*. All these soda-rich minerals crystallize late, and they tend to form spongy plates which are riddled with little enclosures of quartz and feldspar. A change from pyroxene-production to amphibole-production, similar to that which is observed in metaluminous rocks, leads to the earlier crystals of *ægirine* being transformed externally into *arfvedsonite* or *riebeckite*. Typical examples of peralkaline granite are found at Quincy, Massachusetts, occupying an area of about twenty square miles. The chief variety is a light-coloured granite carrying quartz; a microcline-albite microperthite; two varieties of soda-hornblende, one blue (*riebeckite*) and one brown (*cathophorite*), which are often intergrown; green *ægirine*; and accessory *astrophyllite*, zircon, sphene and fluor spar. The *arfvedsonite-ægirine* granites of Norway; the *riebeckite*-granites of Nigeria; and the *ægirine*-granite of Rockall are other well-known examples of this type. The peralkaline granites rarely form bodies of large size, but the number of separate occurrences is not small, and the rocks have a peculiar interest on account of the relative abundance of rare-earths (ceria, zirconia, thorium, etc.) in their composition. The problem of the genesis of these rocks is unsolved.

The original **Tonalite** was the rock of Monte Adamello, south of the Tonale Pass, in the Italian Alps. The rock is coarse-grained and consists of white plagioclase with much quartz, which is mostly in the form of rather rounded bipyramids, and scales of brown biotite

and green prisms of hornblende. The plagioclase has a well-marked zonal structure, the cores of the crystals being much richer in anorthite than the mantles, and the average composition is about $\text{Ab}_{53}\text{An}_{44}\text{Or}_2$. Some free orthoclase is present in graphic intergrowth with quartz, forming interstitial micropegmatite. Little brown garnets, which are not uncommon, probably indicate contamination of the magma with sedimentary material. Accessory minerals are zircon, sphene, magnetite and apatite.

As a whole the tonalites are somewhat less acid than the granites, the content of quartz being in most cases between twenty and thirty per cent. They are also richer in dark minerals, which commonly make up about twenty per cent. of the rock. Tonalites have been described in the Purcell Mts. of British Columbia which carry forty to fifty per cent. of hornblende. The rock of the Marysville batholith in Montana is a more normal tonalite, holding five per cent. of hornblende and seven of biotite. The feldspar which makes up more than sixty per cent. of this rock is one part orthoclase and three parts andesine; and quartz reaches twenty-two per cent. In the tonalites of Electric Peak, in the same state, both pyroxene and hornblende are present, but Iddings has observed that where the rock is coarsest in grain pyroxene disappears and the rock carries hornblende and biotite.

Although most examples of tonalite are metaluminous, the *peraluminous* type is also represented in all the regions mentioned above. Mica-tonalites in the Carpathian Mts. carry from eighteen to twenty-five per cent. of biotite, with plagioclase from five to ten times as abundant as orthoclase. In all other characters these rocks closely resemble biotite-granite. The *subaluminous* type is rare among tonalites, just as it is among granites. An example can be found in the "charnockite" series of Madras. A rock described as a hypersthene-quartz diorite, from the Shevaroy Hills, carries fifteen per cent. of quartz, fifty-five per cent. of andesine (about Ab_3An_1)

twenty-four per cent. of hypersthene and a little iron-ore.

DYSCRYSTALLINE DIVISION.

(*Rhyolite, rhyodacite and dacite.*)

Most oversaturated lavas, and many of the dyke-rocks, are very ill-crystallized. There are generally some insets of quartz and feldspar, which it is easy to identify, but the bulk of these rocks is cryptocrystalline to glassy. Purely qualitative methods of petrography can do little to resolve such rocks as these. So far as mineralogical names have been given to them, they have been based on examination of the insets alone. If the insets are of orthoclase, the rock is called rhyolite; if they are plagioclase, the rock may or it may not be named dacite. In either case the assumption is made that the glassy or cryptocrystalline base of the rock, which possibly constitutes ninety per cent. of the whole, has the same composition as the insets. This assumption is quite unjustified and may be seriously wrong.

In the absence of sufficient mineralogical data, names have often been given which merely express texture. Besides the purely glassy lavas which are called obsidian (and which may have any composition from granitic to tonalitic or syenitic) we have pitchstone, vitrophyre, perlite, felsite, felsophyre, granophyre, pumice and other names. The difficulty of giving any mineralogical interpretation to such names as these has led many petrographers to believe that no systematic classification of cryptocrystalline and glassy rocks is possible without chemical analysis. It is a great merit of the Norm system of classification that rocks of similar chemical composition fall into the same compartments of the classification, whatever their texture may be. Nevertheless, it is quite possible to determine the mineralogical character of a glassy rock without analyzing it, if the specific gravity and the refractive index of the glass are known.

E. S. Larsen measured the refraction and the density of certain mineral glasses with the following results :—

<i>Composition of glass.</i>	<i>Mean R.I. (Na light).</i>	<i>Specific Gravity</i>
Plagioclase {	Ab	1.4890
	Ab ₂ An ₁	1.5166
	Ab ₁ An ₁	1.5307
	Ab ₁ An ₂	1.5452
	An	1.5755
Silica	1.4590	2.213
Enstatite	1.5801	2.758
Diopside	1.6073	2.854

This method has been applied to natural rock-glasses by M. Stark, C. E. Tilley, and W. O. George, who have shown that the refractive index of rhyolitic glasses lies between 1.48 and 1.51, and the specific gravity of the commoner types between 2.1 and 2.4. The peralkaline type, which holds heavy soda-iron silicates, may be 2.5 or even denser. With the additional information given by flame tests or microchemical tests, which show whether soda or potash predominates, it will be seen that most of the requirements of a mineralogical classification can be met without chemical analysis. It is useful to know that the great majority of glassy rocks, including probably all that occur in large dykes and flows, are over-saturated; about three-fifths of them being soda-rhyolites ($\text{Ab} > \text{Or}$), one-fifth potash-rhyolites ($\text{Or} > \text{Ab}$), and one-fifth dacites ($\text{An} > \text{Or}$).

Rhyolites. Many beautiful examples of mica-rhyolite and rhyodacite have been described in Colorado. The rocks are typically porphyritic, having insets of orthoclase and soda-rich plagioclase, as well as a few scales of biotite, in a cryptocrystalline groundmass of quartz and orthoclase. The proportion of biotite is always small; it is commonly two to five per cent., but often no more than a few minute scraps of biotite can be seen in a hand-specimen of the rock. An iron- or man-

ganese-garnet is occasionally present, and shrinkage cavities in some of the rocks are lined with minute crystals of topaz. In some instances tridymite is present instead of quartz.

When a rock is so ill-crystallized that no dark minerals have developed at all, it is still possible to determine the potential mineralogical character by chemical analysis. An obsidian of the Yellowstone Park, analyzed by J. P. Iddings, gave the following norm:—quartz 37, orthoclase 22, albite 33, anorthite 4, corundum 2.2, with a trace of hypersthene and iron ore. If this rock had crystallized, the normative corundum and hypersthene would probably have given about five per cent. of biotite, so in spite of the total absence of crystals the rock may still be described as a peraluminous soda-rhyolite.

A rock which is partly crystalline and partly glassy is more easily classified. A pitchstone from Fifeshire, Scotland, which holds only five per cent. of feldspar insets and a few scales of biotite, was studied under the microscope to determine the character of the feldspar, and the glassy part was examined separately for refraction, density and flame-coloration. The insets were judged to have the composition $Ab_{82}Ab_{18}$; the refractive index of the glass was 1.496, and its density 2.285. This remarkably low density was found to be due to the presence of more than eight per cent. of water in the glass; making a correction for this, the density should be about 2.44. Flame tests showed that the glass contains a large excess of soda over potash, indicating nearly four times as much albite as orthoclase. From these observations it is clear that the rock is a soda-rhyolite, and the presence of a few insets of mica showed it to be a peraluminous variety.

Examples of *metaluminous* rhyolites and rhyodacites have been well described in the San Francisco district of Arizona. The rocks are porphyritic, with a cryptocrystalline base which makes up about three-quarters of the whole. The insets are of plagioclase, biotite, hornblende and sometimes diopside, with a few of quartz. Chemical

analysis shows over twenty per cent. of excess silica and fifteen to twenty of orthoclase, almost all of which is hidden in the glassy groundmass of the rock.

A completely glassy obsidian from Iceland which was examined by F. E. Wright gave a norm in which corundum amounts to 0.6 per cent. and hypersthene to 4.3 per cent. There is too little corundum to convert all the hypersthene into biotite, so if the rock had crystallized it is most likely that an aluminous hornblende, or a mixture of hypersthene and biotite, would have been formed; that is, the rock is potentially metaluminous.

Many examples of *subaluminous* rhyolite have been described in Italy and the Lipari Islands. A typical "liparite," as described by H. S. Washington, is a very fine-grained, ash-grey rock with small insets of pyroxene. The groundmass is microcrystalline and is composed of minute laths of orthoclase, prisms of pyroxene, grains of magnetite, and interstitial quartz. Completely glassy rhyolites from the same region, when analyzed, give norms in which diopside and hypersthene appear without any corundum; they are therefore referable to the subaluminous type. Subaluminous rhyolites are common in the Yellowstone Park region. They have insets of quartz, orthoclase, plagioclase and pale green augite or less commonly hypersthene. The groundmass varies from almost structureless to spherulitic, cryptocrystalline and microcrystalline.

The *peralkaline* type of rhyolite is beautifully developed in the island of Pantelleria, near Sicily, and the name "pantellerite" is almost synonymous with peralkaline rhyolite. There are insets of soda-microcline, and sometimes little prisms of soda-hornblende or soda-diopside, in a microcrystalline to glassy groundmass composed of the same minerals with the addition of quartz. The proportions of these minerals in a typical instance were quartz 30, microcline 51, hornblende (ænimmatite) 12, soda-diopside 7 per cent. Completely glassy rocks of this type are very dark in colour and denser than ordinary

obsidian; and in consequence of the deficiency of alumina, either acmite or sodium metasilicate appears when the norm is calculated. Prof. Daly has described such an obsidian from Ascension Island.

Dacite takes its name from the province of Dacia or Transylvania, in the loop of the Carpathian Mts. In appearance Transylvanian dacites resemble rhyolites, their texture being microcrystalline to glassy. Quartz may appear in well-shaped bipyramidal crystals among the insets, or it may be confined to the groundmass or largely retained in the glassy base of the rocks. The most prominent insets are those of plagioclase, which can easily be confused with orthoclase (the variety sanidine) on account of its glassy appearance and the frequent absence of polysynthetic twinning. The crystals are zonally built but have the average composition of andesine. Biotite, hornblende and pyroxene are all present in the Transylvanian dacites but vary much in their relative proportions; and cordierite and red garnets have been observed in certain cases.

Dacites abound, together with rhyolites and rhyodacites, in the western states of America, especially in the Great Basin region of Nevada. Many of the rocks that have been called dacite, however, contain more orthoclase than anorthite; they are what in terms of our strict definition we should call soda-rhyolite. The "dacite" of Globe, Arizona, has Or 23, Ab 33, An 12; this rock and the "dacites" of Tonopah, Bullfrog, and Silver Peak, Nevada, are soda-rhyolites in our sense. Hornblende-dacite and hypersthene-dacite have been described at Mt. Shasta, California. The former is a light grey rock with a few insets of hornblende. The microcrystalline groundmass consists of plagioclase, hornblende, and a few grains of hypersthene and magnetite, with a little interstitial glass. In the second rock hypersthene is the only dark silicate.

Dacites occur largely in Central America, Colombia

and Ecuador; and dacite was emitted during the eruption of Souffrière, St. Vincent, in 1902. These lavas have insets of strongly zoned plagioclase, augite and hypersthene in a groundmass of feldspar, quartz, tridymite, hypersthene and glass. The plagioclase is a very calcic one, so it is not surprising to find that the proportion of quartz is low, only ten to fifteen per cent.

The lavas of Santorin are black, glassy rhyolites and dacites which carry only a few insets of labradorite and augite. In the glass are many minute needles of albite-oligoclase, a few tiny prisms of augite, and some grains of magnetite. The proportion of free silica is ten to twenty per cent., and some of the lavas have a small excess of alumina which would probably have formed biotite if crystallization had been complete. Many rocks have been described as mica-dacite, but the peraluminous type is rare, biotite being accompanied in nearly all cases by hornblende or a pyroxene.

SUGGESTIONS FOR READING.

- F. F. GROUT, *The Vermilion Batholith of Minnesota*. Journal of Geology, 1925, p. 467.
- J. P. IDDIGS, *Obsidian Cliff, Yellowstone National Park*. Seventh Ann. Rep. U.S. Geol. Survey, 1888. Also Monograph XXXII, 1899.
- W. A. RICHARDSON, *A Micrometric Study of the St. Austell Granite*. Quart. Jour. Geol. Soc., 1923, p. 546.
- C. E. TILLEY, *Density, Refractivity, and Composition Relations of Natural Glasses*. Mineralogical Magazine, 1922, p. 275.
- W. O. GEORGE, *The Relation of the Physical Properties of Natural Glasses to their Chemical Composition*. Jour. of Geol., 1924, p. 353.
- A. BRAMMALL and H. F. HARWOOD, *The Dartmoor Granites*. Quart. Jour. Geol. Soc., 88, 1932, p. 171.
- H. H. READ, *Meditations on Granite*. Proceedings Geologists' Association, 1943, p. 64, and 1944, p. 45.

CHAPTER VI.

ERUPTIVE ROCKS: THE SATURATED CLASS.

The saturated rocks are those that carry neither free silica nor any unsaturated mineral such as nepheline or olivine. Along with the strictly saturated rocks, however, we shall find it advisable (for reasons given on p. 83) to consider those that carry not more than ten per cent. of free silica.

In Zirkel's classification, such rocks were distributed through Classes II., IV. and VII. (see p. 39). Syenite was defined as a rock with alkali-feldspar, without either quartz or feldspathoid. Zirkel recognized, nevertheless, that quartz is often present as an accessory or minor constituent of rocks that he and his contemporaries called syenite. Feldspathoids were nominally excluded from syenite and trachyte but might be present in small amount. The name monzonite was applied to syenitic rocks from the Tyrol, in which plagioclase was present to a large extent. When plagioclase predominated over orthoclase the rock was placed in Class IV., which was subdivided in the following way:—

<i>Composition.</i>	<i>Granular type.</i>	<i>Effusive type.</i>
Plagioclase + hornblende	Diorite	Andesite
„ + augite	Diabase	} Augite-andesite
„ + diallage	Gabbro	
„ + hypersthene	Norite	

In Rosenbusch's system we find saturated rocks in the family of syenitic rocks, the family of dioritic rocks, the family of gabbroic rocks and the family of pyroxenites

and peridotites (see p. 41), as well as in the corresponding families of dyke-rocks and lavas. As usual, Rosenbusch's definitions allow much more latitude than Zirkel's. As regards the syenites, for instance, Rosenbusch not only accepted the presence of quite large quantities of quartz, but even the appearance of "small and also larger" quantities of nepheline or sodalite did not deter him from calling a rock syenite. Among the trachytes, too, Rosenbusch erected a special group of phonolitic trachytes in some of which sodalite was an essential constituent. The syenites were divided into three groups, (a) lime-alkali syenites, (b) alkali-syenites, (c) monzonites. The distinction of lime-alkali syenite from alkali-syenite, like that of lime-alkali granite from alkali-granite, was made to depend rather on field associations than on any specific mineralogical or chemical character. As regards the separation of diorite from gabbro, Rosenbusch introduced a new principle. Instead of basing the distinction on the presence of hornblende or pyroxene, he turned his attention to the character of the feldspar. In the diorites, according to Rosenbusch, the feldspar is oligoclase, andesine or acid labradorite; in the gabbroic rocks it is labradorite, bytownite or anorthite. But Rosenbusch was not consistent even in this, for he described oligoclasites among the gabbros, and put the "napoleonite" of Corsica among the diorites although its feldspar is bytownite. Finally, the name diabase was withdrawn from deep-seated rocks and given to Palæozoic lavas, although diabase was known to be just as often intrusive as effusive. The meaning of andesite was changed to correspond to the new definition of diorite, and basalt was applied to all gabbroic lavas except those of Palæozoic age.

Harker followed Rosenbusch in the use of all the above names, except that dolerite was used in preference to diabase and was applied only to intrusive rocks which are less coarse-grained than gabbro and carry augite in place of diallage.

Iddings followed Rosenbusch in general, but tried to define the names more precisely in the following way:—

Syenite: more than five-eighths of the feldspar is alkali-feldspar.

Monzonite: from five-eighths to three-eighths of the feldspar is alkali-feldspar.

Diorite: less than three-eighths of the feldspar is alkali-feldspar, and the dominant plagioclase is oligoclase or andesine.

Gabbro: less than three-eighths of the feldspar is alkali-feldspar, and the plagioclase is labradorite, bytownite or anorthite.

The names used for the corresponding effusive rocks are trachyte, latite, andesite and basalt respectively.

Hatch and Wells use the names syenite, monzonite and diorite pretty much as Iddings does, but make the dividing ratios two-thirds and one-third; they also restrict the groups in accordance with the silica percentage, as explained on page 42. In the edition of 1926, the principle of separating saturated from undersaturated rocks is accepted as far as the feldspathoidal rocks are concerned.

The Committee on British Petrographic Nomenclature (1921) issued the following recommendations:—

(1) that diorite should be limited to plutonic rocks of intermediate composition, the dominant feldspar being an acid plagioclase; (2) that dolerite should be used in the sense of a coarse-grained rock of basaltic composition, usually but not always hypabyssal, and that diabase should be dropped; (3) that monzonite should be restricted to rocks occurring in the Monzoni district, typically augite-bearing and containing a noteworthy amount of basic plagioclase in addition to orthoclase; (4) that gabbro should include plutonic rocks of basic composition, consisting essentially of a basic plagioclase with one or more ferro-magnesian constituents and . . . with or without olivine; (5) that the term basalt, used alone, should not imply the presence of olivine.

It must be pointed out that the first and fourth of these recommendations are not clear, for we are not told in what sense the terms intermediate and basic are used; and that the second and fifth recommendations are directly opposed to German and American practice.

The present writer is convinced of the importance of defining this class precisely. Strictly speaking, the state of exact saturation is only a boundary between oversaturation and undersaturation—it would be represented diagrammatically by a line separating two fields — and rocks that are exactly saturated with silica should be rare. In reality, owing to the existence of acid and basic silicates and to solid solution (and in part, no doubt, to the limitations of the microscopic method of study), the boundary line expands into a zone of narrow but appreciable width, separated from the oversaturated and undersaturated fields by lines which are “phase-boundaries” of the chemical system. There are no more natural dividing lines than these, and if there is to be any talk of correlating mineralogical with chemical characters these boundary lines—or at any rate one of them—must be recognized in our system and nomenclature.

The boundary between the saturated and the undersaturated state is a phase-boundary for no less than a dozen different minerals (all those on the unsaturated list) and as such it is the most important natural dividing line among eruptive rocks, and should be strictly observed in any system that seeks to express essential rather than trivial characters. Fortunately for us, it is not generally a difficult matter to observe this boundary, for olivine, corundum and garnets stand out in high relief in our thin sections, and feldspathoids and melilite can be detected with acid and dyestuff. It is surprising that a boundary so easily observed and of such significance in terms of the chemistry of the magma should have been steadily ignored by nearly every writer since Zirkel.

The boundary between saturation and oversaturation is of less importance, since it affects only a single mineral

(quartz). It is also difficult to observe, for a small quantity of quartz is not easy to detect under the microscope. We may also take into consideration that certain rocks which have always been regarded as typical examples of syenite, diorite and gabbro actually hold a little quartz; most specimens of the Plauen syenite, for instance, contain five to ten per cent. of quartz. For these reasons we may allow ourselves a little latitude as regards the upper boundary of the saturated class. It is proposed to place that boundary at ten per cent. of free silica. Along with the strictly saturated rocks, then, we shall consider those transitional types which carry no more than ten per cent. of excess silica.

For the distinction of diorite from gabbro, it will be remembered that Zirkel used the nature of the dark minerals, Rosenbusch the nature of the plagioclase. A third method is to distinguish diorite from gabbro by the proportion of light to heavy (dark) minerals. This is no new idea, for it has been the custom for many years to separate anorthosite from gabbro and syenite from shonkinite on this very basis. If we adopt this method, then the subdivision of the plagioclase rocks may proceed as follows:—

Composition of

<i>plagioclase.</i>	<i>Colour-index < 30.</i>	<i>Colour-index > 30.</i>
Ab > An	Soda-diorite	Soda-gabbro
An > Ab	Lime-diorite	Lime-gabbro

Critics of this proposal have found fault with the names used; they say that lime-diorite is not diorite and soda-gabbro is not gabbro. Whether that is so or not depends entirely on whether one follows Rosenbusch or Zirkel. But the names themselves are of no importance; it is the system that matters. If we were to replace lime-diorite by the more familiar name anorthosite, and soda-gabbro by the almost obsolete gabbrodiorite, then we should have diorite, gabbrodiorite, anorthosite and gabbro in place of the double-barrelled names used above, and there would be little possibility of confusion.

In tabular form, the writer's proposal for the subdivision of the saturated rocks (eucrystalline members) is as follows :—

<i>Composition of feldspar.</i>		<i>Leucocratic.</i>	<i>Mesotype and melanocratic.</i>
Or > An	{ Or > Ab Ab > Or	Potash-syenite Soda-syenite	Shonkinite Monzonite
	Ab > An	Soda-diorite	Soda-gabbro
An > Or	{ An > Ab	(diorite)	(gabbrodiorite)
	An > Ab	Lime-diorite (anorthosite)	Lime-gabbro (gabbro)
Without feldspar	—	—	Perknite

Dyscrystalline rocks corresponding to syenite, monzonite, diorite and gabbro are trachyte, trachyandesite, andesite and basalt respectively. Lavas corresponding to shonkinite, anorthosite and perknite are scarcely known.

GEOLOGICAL OCCURRENCE.

Syenite is only found in relatively small masses. It is usually a local facies of a larger body of granite, or else it forms small plugs and dykes which are apparently independent but are very probably offshoots from an underlying granite mass. The well-known Plauen and Meissen syenites of Saxony are local facies of the Meissen granite; the Upsala granite, Sweden, passes locally into syenite; the Beverley syenite of Massachusetts is a facies of the Quincy granite and the Snowbank syenite in Minnesota is an offshoot of the Vermilion granite; the syenite of Bulawayo forms an outlying lobe of the Matopo Hills granite in Southern Rhodesia. At Bancroft and French River, Ontario, syenite is a transitional rock between granite and foyaite (nepheline-syenite), passing gradually into both. There are other cases where syenite is a marginal facies of a larger body of foyaite; this is so

at Pilansberg, in the Western Transvaal, and also at Umptek, Kola Peninsula. In short, the geological occurrence of syenite is such as to suggest that special conditions are required for its formation, and that syenitic magma is not normally present in the earth-crust. The very common association of syenite with nepheline-bearing rocks points to a connection between the origin of syenite and that of nepheline rocks. We shall return to this matter in a later chapter.

The names diorite and monzonite have been used so loosely that it is difficult to establish any generalizations about such rocks. It has already been shown that two quite different principles have been used in distinguishing diorite from gabbro, some writers following Zirkel and some Rosenbusch; and in addition the name diorite has been extended to many rocks that are quite rich in quartz. As soon as we define the name in any precise way, examples of the rock become hard to find. It seems certain that if we merely exclude the quartz-rich diorites (tonalites) from the group, then diorite will be found to be quite as uncommon as syenite. Like the latter, diorite (using the name rather loosely) is often a marginal facies of granite or gabbro, or else it forms small plugs and dykes which have probably been derived from an underlying body of granite or gabbro. Monzonite, too, is a passage facies, not an independent rock. The monzonite of the Tyrol is the middle member of an eruptive series which began with basic lavas, continued with monzonite, and ended with biotite-granite. There are probably no large bodies of dioritic or monzonitic magma.

As for andesite, it is true that great areas of volcanic rocks have been mapped and described under that name, but no conclusion can be drawn from this, for andesite has been more abused than any other rock name. Rocks have been called andesite which, in any precise classification, would fall into every division of the effusive rocks from rhyolite to dacite, trachyte, basalt and even phono-

lite. If the definition of andesite that was proposed above be followed, then these rocks will be found to be little commoner than diorites when similarly defined.

The gabbroic rocks—gabbro, norite, anorthosite and dolerite or diabase—are widely distributed in bodies of large size; and the corresponding lava, basalt, is the most widespread kind of volcanic rock. The great norite sheet of the Transvaal covers more than 12,000 square miles, and in spite of much variation in the proportions of light and dark constituents, the rock is in the main a saturated one. The anorthosite masses of Quebec and Labrador cover some 60,000 square miles altogether, the Saguenay mass alone having an area of 5,800 square miles. These great intrusions are largely composed of saturated rock, although they show local variations just as granite masses do. The Duluth gabbro of Minnesota, with an area of 2,400 square miles, and the economically important Sudbury norite sheet in Ontario (500 square miles) are to a large extent composed of saturated rocks.

Although these figures are comparable with those of granite batholiths, it seems to be well established that the masses referred to have the form of thick sheets or lopoliths, not that of batholiths. The Bushveld sheet is probably three or four miles thick, but it has a well defined sedimentary floor which dips under the lopolith from all sides. The Duluth gabbro is also a floored inclusion—it is the type example of the lopolith—and so is the Sudbury norite. Even the great Canadian anorthosites mentioned above are considered by some geologists to be sheet-like in habit.

Gabbroic rocks also appear on a very large scale as sills and dykes. The rock is not then so coarse in grain as ordinary gabbro and norite, and it receives the name of dolerite or diabase. In the Karroo system of South Africa there is an enormous development of sills and dykes of dolerite, which play such a part in the landscape that it has been said that "one can never get out of immediate sight of dolerité" within an area of more than 220,000 square miles. Individual sheets are often from

a hundred to three hundred feet thick, and they lie one above another with sedimentary partings. The Palisade diabase sheet of New York and New Jersey shows a hundred miles of outcrop and has a thickness of nearly a thousand feet. But large as these figures are, they are surpassed by the extent and thickness of the great basalt plateaux.

The basalt flows of the Deccan, India, cover fully 200,000 square miles, and their combined thickness is four thousand to six thousand feet. The Columbia River basalts of Idaho and Oregon cover 250,000 square miles to a thickness of two thousand to four thousand feet. In the Parana basin of Brazil, Paraguay and Uruguay, the basaltic lava flows have been estimated to contain some fifty thousand cubic miles of rock.

Not all the rocks described as diabase (dolerite) and basalt are strictly saturated. The bigger masses vary a good deal in composition, and they are often olivine-bearing in part.

It is probable that gabbro, norite, dolerite and basalt correspond more closely to the composition of a primary earth-magma than any other rock does.

The anorthosites are sometimes said to be "composed almost entirely of feldspar." That is only true of the more extreme examples, which may hold as little as three to five per cent. of dark minerals; the average anorthosite probably holds about the same proportion of dark minerals as the average granite. It is remarkable that there are no lavas of the composition of the more feldspathic anorthosites. N. L. Bowen lays great stress on this point, and contends that there is no such thing as anorthositic magma, the anorthosites having been formed by accumulation of plagioclase crystals from ordinary gabbroic magma. W. J. Miller takes another view of the matter; he thinks that pyroxene crystals forming in gabbroic magma sank to the bottom of the reservoir, leaving a viscous but still fluid residue which crystallized as anorthosite. On either of these views, anorthosite is derived from normal gabbroic magma.

Rocks that are composed to the extent of ninety per cent. or more of pyroxenes and amphiboles, with iron ores, are called perknite. These rocks are found especially in the form of sheets and lenses within large bodies of syenite, diorite or gabbro; or else they constitute marginal facies of such rocks. The mass of perknite is relatively small in all such cases, and wholly independent intrusions of perknite are not common. In keeping with this there are no lavas of perknitic composition. It has been supposed that perknites are formed by the sinking of heavy crystals from a large body of magma, and their accumulation at a level determined by the density and viscosity of the magma. It is likely that many pyroxene-rocks were formed in this way, but the hornblendites probably have a more complex history. In some of these rocks, every hornblende crystal has a core of pyroxene, or retains some trace of such a core; from which one may conclude that the hornblendite was originally a pyroxenite, and as such it may have originated through the sinking of pyroxene crystals.

There are rocks that consist almost entirely of iron ore (magnetite, ilmenite, chromite, spinel, and various sulphides). It is not generally believed that these bodies crystallized from a magma of their own composition. The problem of their genesis is a very interesting one, but they have more in common with ore-deposits than with eruptive rocks.

MINERALOGY AND TEXTURE.

Among the normal minerals of the saturated rocks are all those that appear in the oversaturated class, although muscovite and tourmaline are uncommon. The plagioclase feldspars show their full range of composition, from albite right to anorthite. In addition, there are varieties of augite and hornblende, known as basaltic augite or titanaugite and basaltic hornblende, which are not found in very siliceous rocks. In general, the dark minerals play a bigger part in this class than in the previous one, and mesotype or melanocratic rocks are so common that

in several cases special names have been coined to distinguish leucocratic from melanocratic varieties.

If quartz is present, it is always among the last products of crystallization. In syenites it generally forms isolated grains in the interstices of the feldspar crystals; in gabbro and diabase or dolerite it is often intergrown with the last of the feldspar, forming micropegmatite.

The feldspars present no new features. A zonal structure is very common, especially in rocks like monzonite and trachyandesite, which carry both alkali-feldspar and plagioclase. In many of these rocks the larger feldspar crystals have cores of andesine or even labradorite, which are surrounded by mantles of albite-rich feldspar, generally anorthoclase. The boundary between core and mantle is irregular, indicating an interruption in the course of crystallization, during which the plagioclase was partly resorbed. When crystallization was resumed, the new feldspar was much richer in soda than the old. Under normal conditions of crystallization the passage from core to mantle should be quite gradual.

Signs of reaction and transformation are observed among the dark minerals too. A change from pyroxene-production to amphibole-production, with transformation of the early-formed pyroxenes into amphibole, is very common, although it is not peculiar to rocks of this class. A reaction which involves the appearance of olivine and its subsequent conversion into pyroxene is often observed in magmas that are only slightly oversaturated. It is known as the Bowen-Andersen effect, after two workers in the Geophysical Laboratory who showed that a melt of the composition of enstatite yields crystals of forsterite when it first begins to crystallize. Under normal conditions of cooling the crystals react with the liquid as the temperature falls, and are converted into enstatite. The temperature at which this transformation takes place in the crucible is 1557° ; but in rock-magmas the transformation temperature is lowered by the presence of other components to such an extent that it falls within the upper

part of the freezing range of the less siliceous magmas. Anything that interferes with the reaction will cause some olivine to be preserved. If, for instance, the olivine grains are enveloped by pyroxene and so withdrawn from contact with the magma, then a little silica will remain uncombined, and when crystallization is complete we shall find olivine and quartz in the same rock; or if the magma is cooled so quickly, after olivine has crystallized, that there is no time for the reaction to take place, then we shall find olivine crystals in a base of siliceous glass. Both cases occur in nature, but the condition is an unstable one. The proper way to deal with such rocks is to compare the proportions of quartz and olivine and see which of them is in excess. In round numbers, two parts by volume of olivine will combine with one part of quartz to form enstatite. In most cases it will be found that there is enough quartz to convert all the olivine into pyroxene, and the rock should then be considered a saturated one.

The *texture* of the deep-seated rocks is granitic to parallel. In diabase (dolerite) the simultaneous crystallization of augite and plagioclase has produced an ophitic texture, which is characterized by the enclosure of laths of plagioclase within large plates of augite. In many diorites and perknites the larger crystals of hornblende, mica or even feldspar are sometimes crowded with little grains of all the other minerals in the rock. This structure, which is described as poikilitic or sieve-structure, may have arisen in some cases by purely accidental enclosure of early-formed grains within later ones; but in other cases it is definitely due to reactions and replacements taking place in the final stages of crystallization.

Trachytes, andesites and basalts are for the most part minutely crystalline, consisting of a mass of tiny laths of feldspar mingled with grains of pyroxene, mica scales, and ore grains. Porphyritic texture is usual in trachytes and andesites, the insets being of ortho-

class in the trachytes and plagioclase in the andesites; along with these there may be some plates of biotite or prisms of hornblende. The majority of basalts are not markedly porphyritic. The groundmass of trachytes, andesites and basalts often holds a proportion of glass, but completely glassy rocks are much rarer than in the oversaturated class and never constitute bodies of large size. Basaltic dykes intruded among sedimentary rocks not infrequently have narrow selvages of glassy basalt or tachylite.

THE ORTHOCLASE DIVISION.

(*Syenite, shonkinite, akerite, monzonite; trachyte and trachyandesite.*)

Syenite, loosely defined, is a coarse-grained rock mainly composed of alkali-feldspar; quartz is only present in trivial quantity, and feldspathoids should be totally absent. Syenitic rocks containing a large proportion of dark minerals have been called shonkinite. Monzonite is a syenitic rock containing much plagioclase in addition to orthoclase. The original monzonite of the Tyrol holds almost equal amounts of light and dark minerals, and a leucocratic rock of the same type, found in Norway, has been called akerite. These three names, shonkinite, monzonite and akerite, should be regarded as subdivisions of syenite. Some authorities prefer to speak of syenite (Monzoni type), syenite (Aker type) and syenite (Shonkin type); there is much to be said in favour of this, but there are times when the briefer forms are more convenient. For lavas fewer names are in use. Any lava of syenitic composition may be called trachyte, and trachyandesite may be used for those of akeritic or monzonitic composition.

The *peraluminous* type of syenite contains biotite as its characteristic dark silicate. With the disappearance of quartz, muscovite becomes uncommon and tourmaline and topaz virtually disappear. Many rocks have been described by the name of mica-syenite, but on close investigation they are generally found to carry a good deal

of quartz, and hornblende is often present in addition to biotite. The syenite of Durbach, which is a marginal facies of the Black Forest granite, has in part the composition of a true mica-syenite. The rock is porphyritic, with insets of orthoclase scattered in parallel position through a groundmass of biotite scales and smaller grains of orthoclase. In places it carries quartz, hornblende or plagioclase. The proportion of mica is high, and some of the rock might be called mica-shonkinite. True mica-syenites, with only five to ten per cent. of biotite and muscovite, occur among the granites of Ontario.

Mica-trachyte is known in a few places and on a small scale, but most trachytes which carry biotite carry hornblende or diopside in addition. Examples of mica-trachyte are not uncommon among dyke rocks; for instance, the dykes of minette or mica-trap which are found in association with granitic rocks in many parts of the world are syenitic to trachytic in character.

The *metaluminous* type of syenite is much commoner than the *peraluminous*. The hornblende-syenite of Plauen, Saxony, has long been accepted as the typical syenite. (The rock of Syene (Assouan), Egypt, which gave rise to the name, is now classed as a hornblende-granite). Soda-orthoclase makes up about three-quarters of the Plauen rock, and green hornblende, accompanied by a little biotite, from fifteen to twenty per cent. Quartz seems always to be present to the amount of five or ten per cent., and as the quartz content increases the rock passes insensibly into the Meissen granite, of which it is a local facies.

The nordmarkite of south Norway is largely a metaluminous syenite, holding both hornblende and biotite, but the proportion of quartz is often so large that the rocks are really sub-acid granites. Beautiful examples of syenite, carrying two or three dark silicates, have been described in Montana and New Hampshire, and in the Monteregian Hills of Quebec. Hornblende-biotite syenites and shonkinites carrying as much as eighty per

cent. of hornblende are developed in connection with the Vermilion and Saganaga granite batholiths (see pp. 62 and 70). All typical examples of monzonite are metaluminous. The monzonite of the Tyrol carries a pale green diopside, green hornblende and brown biotite, also sometimes hypersthene, along with soda-orthoclase and a plagioclase of the average composition of andesine. The proportion of dark minerals is in the neighbourhood of forty per cent., but the composition of the rock varies greatly from place to place. Monzonites occur also in British Columbia, Montana and New Hampshire, in association with trachyandesite. Leucocratic monzonite, or akerite, takes its name from the Aker district of Norway and other examples are known in the Monteregian Hills of Quebec; Tripyramid Mtn., New Hampshire; and near Pretoria, Transvaal.

The majority of trachytes are metaluminous. The widely-known rocks of the Drachenfels and other hills in the Siebengebirge on the Rhine are porphyritic rocks with large insets of sanidine in a pale grey, microcrystalline or partly glassy groundmass. Some acid plagioclase is always present, and among the scanty dark minerals biotite is commonest, but diopside and hornblende are also seen. The crystals of hornblende and biotite often have a corroded appearance and are altered externally into grains of diopside and iron ore. The scanty glass base is highly siliceous and a little quartz or tridymite may be developed in the groundmass. The trachytes of the Auvergne, France, are mainly biotite-trachytes with subordinate hornblende. Many varieties of diopside-biotite trachyte and diopside-hornblende trachyte and trachyandesite have been described in Italy.

The trachyandesites are typically darker in colour than the trachytes. That of Pretoria is a dark grey rock holding a few small insets of plagioclase which are seen, when examined under the microscope, to have broad mantles of anorthoclase round them in which tiny grains of the dark minerals are embedded. The latter are green hornblende, diopside and brown biotite, and they tend to occur in

clusters along with titanomagnetite and apatite, each cluster having a grain of diopside at its centre. The dark minerals make up about 20 per cent. of the rock.

Subaluminous syenites, which carry diopside or augite unaccompanied by hornblende or biotite, are rare. When a pyroxene occurs alone in a syenite it is nearly always an alkaline one—ægirine, soda-diopside, or diopside with mantles of ægirine. In the Laurvik syenite of Norway a brown augite is sometimes the only dark silicate, though it is more usual for this rock to carry some hornblende or biotite in addition. Pyroxene-trachyte, on the other hand, is not uncommon. The pyroxene may be a pale green diopside, a greyish augite, or rarely hypersthene. Such rocks were described by Washington from the island of Sardinia. The trachyte of Monte Arci, for instance, holds insets of soda-microcline in a dense grey base composed of feldspar with a little quartz and about ten per cent. of augite and magnetite.

The *peralkaline* type is well represented in Finland and Scandinavia. At Umpjek in the Kola Peninsula a syenite composed of microperthite with arfvedsonite and ægirine forms a border facies of a great body of nepheline rocks. The syenite of Almunge, Sweden, carries two different soda-amphiboles, a brown arfvedsonite and a blue-green hastingsite. Many examples of ægirine- and arfvedsonite-syenites and shonkinites have been described in the Christiania (Oslo) district of Norway.

The peralkaline granite of Quincy, Massachusetts, passes into the Beverley syenite, a rock which is almost free from quartz and carries either ægirine or soda-hornblende, with accessory biotite, magnetite and sphene. The rock of Wigwam Quarry holds seventy per cent. of sodi-potassic feldspar, eight per cent. of quartz, and twenty-two per cent. of ægirine and riebeckite.

Peralkaline trachytes are well developed in eastern Australia and New Zealand. The trachytes of the Nandewar Mts. carry ægirine and a deep blue hornblende, with soda-rich feldspar and sometimes a little

quartz. Ægirine-trachytes occur on Mt. Flinders and in the Canobolas Mts., and arfvedsonite-riebeckite trachyte in the Glasshouse Mts. Trachytes composed of soda-orthoclase, soda-diopside and magnetite, with very little quartz, are developed near Dunedin, New Zealand. Similar lavas with ægirine, cossyrite, and fayalite are widely distributed about the Great Rift Valley, in Kenya.

THE PLAGIOCLASE DIVISION.

(*Diorite, gabbro, anorthosite, norite; dolerite (diabase), andesite and basalt.*)

The meanings attached to the names diorite and gabbro, andesite and basalt, by Zirkel and by Rosenbusch, have been explained, and an alternative proposal was put forward on p. 83. Whatever system one follows, the most typical diorites—those composed of oligoclase and hornblende—remain diorites and the most typical gabbros—those composed of labradorite and pyroxene—remain gabbros; while as for the anorthosites, if one calls them by that name it is quite unimportant whether they are regarded as a subdivision of the diorites or of the gabbros. Dolerite and diabase are synonymous terms for fine-grained gabbro or coarse-grained basalt; and norite is just hypersthene-gabbro and ought never to have received any other name.

Rocks of peralkaline type do not occur in this division, and peraluminous varieties are very scarce. The name mica-diorite is quite widely used in petrographical literature, but most of these rocks either hold so much quartz that they are really tonalites or else they carry hornblende in addition to biotite. Mica-andesites which contain no hornblende are equally scarce, in spite of the common use that has been made of the name.

Metalluminous varieties of diorite and soda-gabbro are common enough, usually in association with great intrusions of granite, granodiorite and tonalite. Hornblende-plagioclase rocks of variable composition occur among the border-facies of the Vermilion granite (p. 62)

and the Saganaga granite (p. 70); and quite similar rocks are developed in connection with the granodiorites and tonalites of Montana. Diorites of very variable composition occur at Electric Peak in the Yellowstone National Park. Both hypersthene and augite are present, along with hornblende, biotite, plagioclase, orthoclase and little or much quartz. In Europe, the Brünner tonalite mass in Austria has marginal facies rich in plagioclase, hornblende and biotite. The biotite-granite of Sark, Channel Islands, passes locally into rocks composed of oligoclase and hornblende in almost equal parts. All such rocks as these are diorite in the sense of Rosenbusch, but the colour index is abnormally high.

Hornblende- and hornblende-biotite andesites have been described in North and Central America, the Andes, Hungary, Spain and elsewhere, but in absence of quantitative detail one can never be sure what the precise mineralogical composition of these rocks is. Some of them are certainly rhyodacites and dacites. The lavas of Electric Peak and Sepulchre Mtn., Yellowstone National Park, have been described as andesite, although some of them are rather strongly oversaturated. They vary from microcrystalline to hypocrySTALLINE, the majority having more or less of a dark-coloured glassy base. Augite, hornblende and biotite are all present, but hornblende and biotite increase in abundance as augite diminishes.

Hornblende-basalt is not common. An interesting example has been described at Bill Williams Mtn., Arizona. The visible constituents of this rock are hornblende (48 per cent.), labradorite (12 per cent.) and magnetite (2 per cent.), and there is a cryptocrystalline groundmass which makes up the remaining 37 per cent. of the rock. Chemical analysis shows that if the rock had crystallized completely it would have had approximately the following composition:—quartz 7, plagioclase 42, hornblende 48, magnetite 2 per cent. Although the insets are of labradorite, the total plagioclase has the composition of oligoclase, so the groundmass must consist almost entirely of quartz and albite.

Among anorthosites, gabbros and basalts the *sub-aluminous* type predominates greatly. Many of the greatest gabbro and norite masses are subaluminous throughout, and in others hornblendic and biotitic facies are only of local occurrence. The pyroxene may be rhombic or monoclinic, or it may belong to the intermediate group of the enstatite-augites. Parallel intergrowths of rhombic and monoclinic pyroxene are also known. Some of these rocks carry a little quartz and orthoclase, and some hold a few grains of olivine which are enclosed in pyroxene and have consequently escaped resorption; but the main constituents are always labradorite and some kind of pyroxene. In coarse-grained gabbros the pyroxene has the habit of diallage, with an almost micaceous cleavage parallel to one of the pinacoids; in the norites it is hypersthene, which may be associated with augite or diallage. In the dolerites (dibasites) and basalts the pyroxene may be of any kind without affecting the name of the rock.

Prof. R. A. Daly has written of the great norite sheet of the Bushveld Complex, in the central Transvaal, that "for vastness of scale and for drastic results of differentiation in place, it seems to be without a peer among the known rock bodies in the world." The upper eight or ten thousand feet of the sheet consist of a fairly homogeneous norite of medium to coarse grain, the crystals being commonly from a quarter to half an inch in diameter. It weathers with a dark brown crust, but the fresh rock is rather light grey in colour, consisting of a white feldspar and a dark grey pyroxene in nearly equal proportions. The feldspar is a labradorite holding about sixty-five per cent. of anorthite. The pyroxene is partly hypersthene (bronzite) and partly diallage, the two being often intergrown and sometimes ophitic towards the feldspar. Many specimens hold nothing else, except a trace of apatite or iron ore, but sometimes a little hornblende or biotite has been formed about the margins of the hypersthene crystals. In the lower half of the sheet the

norite is strongly differentiated, passing on the one hand through bronzite-rich norite into pyroxenite (bronzitite) and on the other hand through feldspathic norite into anorthosite.

Most anorthosites hold rhombic or monoclinic pyroxene, but hornblende is common, and an iron-magnesium garnet is an important accessory in some anorthosites. The feldspar is usually bytownite or labradorite, but it may be andesine or even oligoclase. An andesine-anorthosite has been described in Virginia; besides the dominant plagioclase it holds a little microcline and quartz, with hypersthene, rutile, ilmenite and apatite. The Bushveld anorthosites form bands and lenses within differentiated norite. The rocks are blue-grey to white in colour and look much like marble in the field. They are composed of interlocking grains of a very calcic plagioclase, containing nearly ninety per cent. of anorthite, with only trifling amounts of a pale-coloured pyroxene, apatite, pyrrhotite and chromite. As much as ninety-seven per cent. of the rock may be feldspar.

South Africa contains another huge formation of gabbroic rocks, in the form of dolerite sills which outcrop everywhere through a quarter of a million square miles. The composition of these rocks is very simple, about nine-tenths of each rock being composed of plagioclase and augite, generally in ophitic intergrowth, together with a little titanomagnetite. In the interstices there may be a little micropegmatite of quartz and orthoclase, and sometimes a few grains of olivine have been enclosed in augite and so prevented from reacting with the excess of silica. The average composition of these rocks might be expressed as labradorite 40 to 50, augite 30 to 40, orthoclase 0 to 5, quartz 0 to 5, olivine 0 to 5, titanomagnetite 2 to 10 per cent. The same figures might stand for the composition of dolerite (diabase) anywhere in the world. They compare very closely with the figures given by A. Holmes for the Whin Sill and related dykes of the North of England.

Augite- and hypersthene-andesites in the sense of Rosenbusch are common lavas, but most of them hold so much pyroxene that the writer would prefer to call them basalt. The andesites of the San Francisco volcanic district in Arizona are interesting as showing olivine crystals in a glassy base which contains enough free silica to have converted all the olivine into pyroxene if the cooling had taken place more slowly.

Basalts show about the same range of composition as diabase (dolerite). The basalts of the Deccan, India, are remarkably alike in character all over the huge area of 200,000 square miles which they cover. They are dense, non-porphyrific rocks with less than ten per cent. of interstitial glass. The mineralogical composition, calculated from analyses by H. S. Washington, is roughly as follows:—quartz 2 to 5, orthoclase 5 to 7, labradorite 40 to 50, pyroxene 30, and iron ores up to 12 per cent. Quite similar figures are given for the Snake River basalts in Oregon and for the basalts of Iceland and the Faroe Islands. The texture of basalts is more commonly granulitic than ophitic; that is, it is characterized by rather rounded grains of augite caught in a network of felspar laths, with or without some dark-coloured interstitial glass. Gas vesicles are often developed, the larger ones being many feet in diameter. These are lined with beautiful crystals of various zeolites, and agates are also common in such rocks.

THE HYPERMELANIC DIVISION.

(*Perknites, pyroxenites, hornblendites.*)

We include under the name of perknite all saturated rocks which are composed to the extent of nine-tenths or more of pyroxene, hornblende, biotite, and oxidic or sulphidic ores. Such rocks are generally called pyroxenite or hornblendite, but more specific names are also in use, such as hypersthene, diallagite, etc. Perknites do not constitute independent rock masses; they are typically differential facies of other rocks, which may

range from granite to gabbro. Hornblendites are mostly found in association with rather acidic rocks, pyroxenites with gabbros and norites. Hornblendites are associated with the Vermilion and Saganaga granites (pp. 62 and 70). It is sometimes possible to show that hornblendites have been formed by the transformation of pyroxene into hornblende; the process has been well described in rocks of Garabal Hill, Scotland.

An occurrence of pyroxenite which has become classic since its description by Prof. W. C. Brögger is found in the parish of Gran, Norway. In this neighbourhood there are several bosses of a monzonitic rock containing orthoclase, labradorite and augite. About the margins of the bosses the augite has been concentrated at the expense of other minerals, giving rise to a rock that consists of as much as 95 per cent. of augite, with only trifling quantities of hornblende, biotite and feldspar.

Pyroxenites consisting almost wholly of ortho-pyroxene (hypersthene or bronzite) are largely developed in the deeper layers of the Bushveld norite, and entirely similar rocks occur in the Great Dyke of Southern Rhodesia and in the Stillwater complex of Montana. Some of these rocks carry a little diopside and chromite, but many thin sections show nothing but hypersthene. Some pyroxenites hold a good deal of oxidic or sulphuric iron ores. At Glamorgan, Ontario, a heavy pyroxenitic rock consisting of augite and titanomagnetite in about equal parts has been worked as an iron ore.

The conditions of formation of perknites stand greatly in need of further investigation.

SUGGESTIONS FOR READING.

- A. L. DU TOIT, *The Karroo Dolerites of South Africa*. Trans. Geol. Soc. S. Africa, vol. 23, 1920, p. 1.
H. S. WASHINGTON, *Deccan Traps and other Plateau Basalts*. Bull. Geol. Soc. America, vol. 33, 1922, p. 765.
N. L. BOWEN, *The Problem of the Anorthositic*. Jour. of Geol., vol. 25, 1917, p. 209.

- O. ANDERSEN and N. L. BOWEN, *The Binary System MgO-SiO₂*. Amer. Jour. Sci., vol. 37, 1914, p. 487.
- J. P. IDdings, *The Eruptive Rocks of Electric Peak and Sepulchre Mountain*. Twelfth Ann. Rep. U.S. Geol. Survey, 1891, p. 569.
- R. A. DALY, *Bushveld Igneous Complex of the Transvaal*. Bull. Geol. Soc. America, vol. 39, 1928, p. 703.
- A. HOLMES, *The Age and Composition of the Whin Sill*. Mineralogical Magazine, vol. 21, 1928, p. 493.

CHAPTER VII.

ERUPTIVE ROCKS—THE UNDER-SATURATED CLASS

(NON-FELDSPATHOIDAL GROUP).

This group contains rocks in which the alkalis are saturated with silica but some of the magnesia, lime or alumina is unsaturated. The characteristic minerals of the group are olivine, melilite, corundum, melanite, pyrope and perovskite. Of these only the first has any quantitative importance.

None of the larger divisions of Zirkel's system was based on the presence or absence of olivine, but within Classes IV and VII the olivine-bearing rocks were separated from the olivine-free. No new names were given to them, the hyphenated forms olivine-gabbro, olivine-diabase and olivine-norite being thought distinctive enough. The effusive rock corresponding to these was called basalt (or sometimes feldspar-basalt to distinguish it from nepheline-basalt). No prefix was needed in this case because the name basalt definitely implied the presence of olivine, a plagioclase-augite rock without olivine being called augite-andesite.

Rosenbusch followed similar lines in separating the olivine-free members of his family of gabbroic rocks from the olivine-bearing ones, naming them simply olivine-gabbro and olivine-norite. As regards the use of the term basalt, he says expressly that "if one speaks simply of basalt, one means olivine-basalt." Iddings, too, follows Zirkel's practice in this matter; he writes of basalt and olivine-free basalt, giving the latter the alternative name of labradorite-andesite.

British writers have reversed this procedure. Harker, Hatch, Holmes and Tyrrell all describe basalt as being typically free from olivine; and the British Petrographic Nomenclature Committee recommended in 1921 that "the term basalt used alone should not imply the presence of olivine. Basalts containing olivine as an essential constituent should be described as olivine-basalts."

It is interesting to notice that the fashion of creating new specific names, which has been carried to such lengths in other groups of rocks, has left the olivine-bearing group almost untouched. Although no less than four names (gabbro, diabase, norite and hyperite) are used to express a change in the character of the pyroxene of gabbroic rocks, from diallage to augite and hypersthene, yet the appearance of the new mineral olivine is only marked by the use of a hyphen. This is a case when the introduction of a new name would have been justified, for the appearance of olivine in a rock indicates the crossing of a significant chemical boundary.

As regards the other characteristic minerals of this group, most authorities put the melilite rocks in a special subdivision, but no significance from the point of view of classification has ever been attached to corundum, melanite, pyrope or perovskite.

The present writer would subdivide this group of rocks on the same lines as the saturated class (see p. 84). There being no distinctive group names in existence, one must just continue to use the names of the saturated rocks, adding the appropriate prefix, as olivine-gabbro, melanite-syenite, corundum-anorthosite, and so on. If a group name is required, a provisional one may be made by putting the prefix sub- before the rock name; thus sub-syenite may stand for the group which contains the species melanite-syenite, corundum-syenite and olivine-syenite.

GEOLOGICAL OCCURRENCE.

Only the olivine rocks form large geological masses. Some of these are feldspar-bearing (olivine gabbro or

norite, and olivine-basalt), others are free from feldspar (peridotite and serpentine). The great mass of olivine-norite which builds up the peninsula of Sierra Leone has an area of at least two hundred square miles, and olivine is distributed fairly uniformly, to the amount of ten or fifteen per cent., through the whole mass. In places the rock tends to be banded, some of the bands being richer in feldspar and others richer in olivine. The Duluth gabbro, in Minnesota, is also banded and some of the bands contain olivine.

The great sheets of olivine-gabbro or norite at Insizwa and Tabankulu in South Africa are each fully half a mile thick, and A. L. du Toit considers that the original sheet of which these are only relics covered not less than seven hundred square miles. The Tabankulu sheet is olivine-bearing throughout its whole thickness, but the concentration of olivine increases downwards to such an extent that the specific gravity of the rock at the base of the sheet is 3.27, that at the top being 2.91. A similar downward concentration of olivine is noticeable at Insizwa, where the base of the sheet is a dark, heavy rock composed of pyroxene and olivine with little feldspar, while the top of the sheet is an olivine-free gabbro which carries a little quartz. The tendency of the magma to become differentiated into olivine-rich and olivine-poor fractions, which is clearly demonstrated in these cases, finds a still more remarkable illustration in the Island of Rum, Scotland, where A. Harker described a hill (Allival) built up of nineteen nearly horizontal layers alternately composed of olivine-rock (peridotite) and of olivine-anorthite rock (allivalite).

In the Insizwa and Tabankulu sheets, and in other sheets of similar structure and composition in many parts of the world, the olivine crystals are believed to have formed in the magma at an early stage and to have sunk under their own weight (gravitational differentiation or crystal-settling). In the case of the Allival sheets, Harker supposes that differentiation took place below the

level of intrusion, and that lighter and heavier fluids were injected alternately.

Many great sheet-intrusions in addition to those named above carry olivine in part; thus the Palisade diabase sill of New Jersey has a zone of olivine-rich diabase about fifty feet above its base, but this facies only makes up about one per cent. of the thickness of the sheet. An admirably complete study of the gravitational concentration of olivine in this sill has recently been made by F. Walker who has also studied the same phenomenon in the Shiant Islands, Scotland.

Among the effusive rocks of the continents, olivine-basalt is nearly as common as olivine-free basalt, although loose use of the name basalt to cover both olivine-bearing and olivine-free rocks makes it difficult to test this conclusion statistically. The lavas of the oceanic islands, especially the enormous pile which rises about 30,000 feet from the ocean floor to form the island group of Hawaii, are very largely olivine-basalt.

Among the olivine-rich rocks which are nearly free from feldspar, we have already seen that some appear to have been formed by the sinking of olivine crystals out of a feldspathic magma, and their accumulation at or near the base of the intrusive body. But there are peridotites which are definitely intrusive on their own account and seem to owe nothing to crystal-settling. These form stocks, pipes and dykes, some of which are of very large size. In the Great Serpentine Belt of New South Wales, various types of peridotite and serpentine form a chain of outcrops which extend for a total distance of nearly two hundred miles along the line of a powerful fault. Feldspathic rocks such as olivine-gabbro and anorthosite play a very minor part in this complex. The Great Dyke of Southern Rhodesia, an immense dyke-like body three hundred miles long and five miles wide, is also composed very largely of hypermelanic rocks such as pyroxenite and peridotite, with only a subordinate development of norite.

Stock-like bodies of peridotite within larger intrusions of olivine-gabbro are largely developed in the Ural Mts. Round a core of peridotite there is a zone of more pyroxenic peridotite, then one of melanocratic gabbro which passes out into normal gabbro. These remarkable zoned intrusive bodies are paralleled on a smaller scale in the eastern Transvaal, where there are pipe-like bodies of a dark, iron-rich peridotite, surrounded by a zone of magnesian peridotite, then sometimes by a zone of pyroxenite, which passes out into ordinary norite. The meaning of this extraordinary zonal arrangement has not been made clear.

The diamond-bearing kimberlite pipes of South Africa are independent intrusive bodies mainly composed of olivine and serpentine, occupying the throats of former volcanoes. Nearly three hundred such pipes, ranging in size from the Premier mine, with a diameter of a thousand yards, down to pipelets only a few yards across have been located in the Union of South Africa alone, and many more are known in South-West Africa, Rhodesia, the Congo territories and East Africa.

Thus, although there is a definite group of "accumulative peridotites" which were not formed from a magma of their own composition, the other group of "intrusive peridotites" and serpentines establishes the existence of olivine-rich magma in the crust of the earth. When one takes into account, too, the olivine-gabbros and norites, olivine-diabases and olivine-basalts, then it becomes clear that undersaturated magnesian magma is one of the more important structural materials used in the building of the earth.

One cannot say this of the other rocks that fall in the present group. Corundum is almost confined to certain syenitic and dioritic pegmatites and aplites which are restricted in distribution and relatively insignificant in bulk. The corundum reefs of the Transvaal are coarse pegmatites which carry quartz and mica where they cut granite and only become corundiferous when they enter

basic magnesian rocks. The conditions under which corundum occurs in the United States and in the Ural Mts. are almost identical with those in the Transvaal. The corundum-pegmatites of eastern Canada are derived from granite masses which invade a country of limestones and amphibolites. These facts clearly indicate that corundum is a product of some special reaction, for no normal magma carries such an excess of alumina as to give rise to corundum. In dyke-rocks and lavas a small content of corundum is sometimes a result of assimilation of aluminous sediments.

Rocks containing melilite are very rare and they are almost always found in small pipes, dykes, and insignificant surface flows. The melilite basalts have clearly crystallized from a magma of their own composition, but it is also clear that this magma is so rare that it can only have been formed by some special reaction from a more usual type of magma. The association of melilite rocks with thick limestones is so conspicuous, notably in Germany, Bohemia and eastern Canada, as to have led some authorities to believe that melilite is a product of the assimilation of limestone. A plug of melilite-basalt that cuts dolomite in Missouri has recently been studied by Singewald and Milton, who find strong evidence of reaction and solution of dolomite in the magma. It is true that there are some occurrences of melilite-basalt in regions where no limestone is visible, but then one never knows what a magma has come into contact with far underground. At all events, it is certain that melilite magmas are abnormal and of no quantitative importance.

Melanite or andradite (calcium-ferric garnet), a minor constituent of many feldspathoidal rocks, is sometimes present in syenites which contain no feldspathoids at all. It only becomes abundant in some rare types of melanocratic syenite, as at Loch Borolan, Scotland; Poohbah Lake, Ontario; and Sviatoy Noss in the Transbaikal region. There is strong reason to believe that the

mineral is formed in consequence of assimilation of limestone by alkaline magmas.

Pyrope is a minor constituent of some peridotites and serpentines, such as the kimberlite of South Africa; and perovskite is an accessory mineral of melilite and nepheline rocks.

MINERALOGY AND TEXTURE.

In addition to the six minerals that are characteristic of the group, any mineral that occurs in the saturated class—that is, any variety of feldspar, pyroxene, amphibole or mica, but neither quartz nor any feldspathoid—may appear in this group of rocks. As regards quartz, there is the usual exception to be made that a small quantity of quartz may be present in consequence of the Bowen-Andersen effect, as explained on page 89. In most cases where quartz and olivine appear in the same rock there is enough quartz to combine with all the olivine present, but sometimes olivine is in excess, and then the rock must be judged to belong to the present group in spite of the presence of a trace of free silica.

Olivine is almost always a mineral of early crystallization. In coarse-grained rocks the olivine crystals are often enclosed in larger crystals of augite, mica or feldspar, giving a poikilitic texture to the rock. When the quantity of olivine is small and it is associated with a strongly calcic plagioclase, the olivine crystallizes later and may be moulded on the feldspar. In lavas olivine crystallizes early and does not ever seem to be retained in the glassy base; it forms conspicuous little insets which may become grouped together to form nodules of comparatively large size. In most olivine-bearing rocks the beginning of the alteration of olivine into serpentine can be observed. Greenish or grey minutely fibrous serpentine grows about the margins of the olivine grains and along cracks in the interior, and at a later stage an entire crystal may be converted into a mass of serpentine in

which only a few rounded grains of olivine survive. The peculiar mesh-structure that persists when the whole of the olivine has been changed makes it easy to recognize serpentine that has been formed from olivine. Other magnesian minerals such as enstatite and hornblende may also undergo serpentinization.

Melilite is almost always confined to the groundmass of a rock, and forms little laths which show very weak birefringence. It is most easily identified by gelatinizing with acid and staining with an aniline dye.

Corundum forms hexagonal prisms and barrel-shaped crystals in some pegmatites. It is seldom found under any other circumstances, but grains of sapphire are occasionally seen in basaltic flows and dykes which have assimilated sedimentary material.

Melanite crystallizes in rhombic dodecahedrons. The colour is brown to yellow in thin sections; it is sometimes distributed in zones which are parallel to the contours of the crystals. Some melanite is very rich in titania, and then crystal outlines are usually lacking. The transformation of titaniferous melanite into sphene has been observed.

Perovskite forms tiny yellow octahedrons in the groundmass of some melilite and nepheline rocks. Pyrope is confined to peridotites and serpentines; the crystals are rounded and enveloped by a mantle of hornblende prisms and other reaction-products.

THE ORTHOCLASE DIVISION.

This division is very scantily represented. Corundum, melilite and melanite are rare minerals, and olivine is very seldom associated with orthoclase, presumably because the molecules of these minerals can react to form biotite and hypersthene.

The *peraluminous* type is represented by the corundum-syenites and pegmatites of Ontario, which have a soda-rich microporthite as their feldspar. The only heavy

minerals besides corundum are white and black mica and rarely a little hornblende. Microperthite-corundum rocks with subordinate mica are also found in the Ilmen Mts. and in Madras.

A syenite of *metaluminous* type, containing soda-orthoclase together with olivine, brown hornblende and biotite, has been described at St. Hilare Mt., Quebec. Monzonites carrying olivine and biotite are known at Smalingen, Sweden, and at Kentallen, Scotland. The latter rock holds well-formed crystals of augite and olivine, with plates of biotite of late crystallization, in a groundmass which consists of orthoclase and sodic plagioclase in roughly equal quantity.

Olivine-trachytes and trachyandesites of *subaluminous* type have been described in a few instances. Lavas of Monte Cimini, Italy, carry augite and about ten per cent. of olivine, with soda-orthoclase and plagioclase. Olivine is also present in some varieties of the trachyte of Mont Dore, Auvergne.

The *peralkaline* type is represented by the rare melanite-ægirine syenites. A coarse-grained melanite-syenite at Poohbah Lake, Ontario, consists of large, flesh-coloured crystals of microperthite which are embedded in a greenish matrix of feldspar, soda-pyroxene, melanite, biotite, sphene and apatite. Rocks of similar mineralogical character have been found at Loch Borolan and Loch Ailsh in north Scotland, and at Sviatoy Noss, Transbaikalia.

THE PLAGIOCLASE DIVISION.

The plagioclase-corundum rocks of the Transvaal, of Plumas County, California, and of Dungannon, Ontario, are *peraluminous* diorites and soda-gabbros. Some of these rocks hold little but oligoclase and corundum, but others have biotite in addition. The corundum-anorthosite of Kyschtym, Ural Mts., has anorthite for its feldspar and biotite and spinel as accessory constituents.

Metaluminous rocks are quite uncommon in this

group. Under the name of *essexite* certain rocks have been described in Norway and in the Monteregian Hills of Quebec which consist of a calcic plagioclase together with some alkali-feldspar, and augite or hornblende, biotite and olivine. They have little quantitative importance.

Among the *subaluminous* members of this group, those with a soda-rich plagioclase are scarce. Such a rock has been described from Hawaii under the name of *kauaiite*. It is coarse-grained and composed of large tables of plagioclase with a zonal structure, the average composition being andesine. The dark silicates are pyroxene and olivine, and an unusually large proportion of titanomagnetite and apatite is present. The rock is a soda-gabbro. Soda-basalts have been described in the Isle of Skye, under the name of *mugearite*. These are dark, compact rocks without insets of any kind, closely resembling ordinary basalts. Under the microscope the feldspar is seen to be oligoclase, with subordinate orthoclase. Olivine is the principal heavy mineral, but iron-ore and augite are present in small quantity and there is an unusually large proportion of apatite. Harker gives the mineralogical composition of a typical *mugearite* as follows:—oligoclase, $57\frac{1}{2}$; orthoclase, $12\frac{1}{2}$; olivine, ore and augite, $26\frac{1}{2}$; apatite, $3\frac{1}{2}$ per cent. These rocks carry so much orthoclase that they approach trachyandesite in composition.

The great majority of olivine-bearing rocks belong to the lime-gabbro family. Common varieties of olivine-gabbro, olivine-norite and olivine-dolerite (diabase) hold ten to fifteen per cent. of olivine along with fifty to sixty of labradorite, the remainder consisting of rhombic or monoclinic pyroxene and iron-ore. The olivine has generally crystallized early and forms well-shaped or slightly rounded crystals which may be enclosed in younger crystals of pyroxene. The pyroxene, whether rhombic or monoclinic, is usually ophitic towards the

feldspar. In some cases the olivine, too, is moulded on feldspar crystals. Harker has shown in the case of olivine-anorthite rocks that it depends entirely on the relative proportions of the two minerals whether olivine or anorthite crystallizes first.

Typical examples of olivine-gabbro, of which good descriptions are available, are those of Cuillin Hills, Isle of Skye; of the Lizard, Cornwall; of Duluth and Pigeon Point, Minnesota; of Sierra Leone, West Africa.

When the proportion of dark minerals rises to a high figure, the name picrite is often given to the rock. Picrites with forty to seventy-five per cent. of olivine have been described in Skye. The picrite of Tabankulu, South Africa, is composed to the extent of one-third to two-thirds of well-shaped crystals of olivine which are enclosed in larger crystals of pyroxene and feldspar. Both ortho- and clino-pyroxenes are present, and the feldspar is labradorite to bytownite.

Rocks containing only plagioclase and olivine are known as troctolite. The banded peridotites of Rum, Scotland, are composed of anorthite and olivine in all proportions from pure olivine-rock to pure anorthite-rock.

Olivine-basalts occur abundantly in the Siebengebirge, the Eifel and the Auvergne; in Ulster and the Hebrides; in the Canary Islands and Madeira; in the Sierra Nevada, Oregon and Arizona. The olivine-basalts of Hawaii may be taken as representative of the group. These lavas, although they are loosely described as basalts, actually differ a good deal among themselves, some being free from olivine and others containing orthoclase, nepheline or melilite. The plagioclase ranges from albite to bytownite, but it is mostly labradorite or andesine and often has nearly the composition Ab_1An_1 . The rocks are generally dark in colour and microcrystalline to glassy in texture; many varieties are porphyritic, some having insets of labradorite but the majority insets of olivine and augite. The olivine crystals are occasionally more than a centimetre in diameter. The groundmass is

composed of plagioclase, augite and magnetite, often unaccompanied by olivine, but those rocks that have insets of plagioclase may have some olivine in the groundmass. Sometimes there is no more olivine than can be accounted for by the Bowen-Andersen effect.

Basalts carrying an unusually large proportion of olivine are called chrysophyre or picrite-basalt. Cross describes a chrysophyre of the island of Oahu, in the Hawaiian group, which is composed to the extent of nearly two-thirds of olivine. Rhombic pyroxene also appears among the insets in this rock, but the groundmass contains only augite, plagioclase and magnetite. It appears to be a common feature of Hawaiian lavas that more olivine is present in the rock than in the norm calculated from analysis. This indicates that some free silica must be present in the groundmass.

THE HYPERMELANIC DIVISION.

(*Peridotites, dunites, melilite-basalts.*)

The most general name for a rock composed to the extent of ninety per cent. or more of heavy minerals, including olivine, is peridotite. The minerals associated with the olivine are various pyroxenes, hornblende, biotite and iron-ores. When olivine itself makes up nearly the whole of the rock the name dunite (derived from Dun Mtn. in New Zealand) is used. Some hypermelanic rocks are rich in lime and carry melanite or melilite instead of olivine, but these are extremely rare rocks. There are no effusive rocks properly corresponding to the peridotites and dunites, but the rare melilite-basalts approach this composition.

Hornblende-rich peridotite is not uncommon on a small scale; some such rocks carry only hornblende, olivine and a little magnetite. A dark mica (biotite or phlogopite) may be present along with the hornblende, and so there is a transition to the mica-rich peridotites or kimberlites. The commonest type of peridotite is one which carries hypersthene and olivine; it is known by the varietal name of harzburgite.

The dunite of New Zealand is almost a pure olivine-rock, little grains of chromite and scanty crystals of diopside being the only other constituents. In most dunites the olivine is the common magnesian variety, but in the eastern Transvaal there are pipes of a dark brown, very heavy dunite composed of olivine in which the forsterite and fayalite molecules are present in roughly equal quantity. The only other minerals are a little hornblende, diopside and ore, with native platinum as an interesting but extremely scanty accessory constituent.

Melilite-basalts are fine-grained, very dark coloured rocks which may carry little insets of olivine or sometimes large scales of biotite. The groundmass consists of tiny laths of melilite, scales of mica, grains of augite and ilmenite, minute octahedrons of perovskite and usually some calcite and interstitial glass.

Kimberlite, the matrix of all African diamonds, is a highly serpentinized rock containing usually a great deal of phlogopite together with residual grains of unserpentinized olivine and fragments of ilmenite, pyroxene and garnet (pyrope).

In many respects kimberlite resembles melilite-basalt, of which it may be a serpentinized variety.

SUGGESTIONS FOR READING.

- F. DIXEY, *The Norite of Sierra Leone*. Quart. Jour. Geol. Soc., vol. 78, 1922, p. 299.
- A. HARKER, *Geology of the Small Isles of Inverness-shire*. Mem. Geol. Survey Scotland, 1908.
- A. HARKER, *The Tertiary Igneous Rocks of Skye*. Mem. Geol. Survey Scotland, 1904.
- F. WALKER, *The Geology of the Shiant Isles*. Quart. Jour. Geol. Soc., vol. 86, 1930, p. 355.
- W. CROSS, *Lavas of Hawaii and their Relations*. U.S. Geol. Survey, Prof. Paper no. 88, 1915.
- J. S. FLETT, *The Geology of the Lizard*. Mem. Geol. Survey England, 1912.
- F. F. GROUT, *A Type of Igneous Differentiation*. Jour. of Geol., vol. 26, 1918, p. 626.
- F. WALKER, *Differentiation of the Palisade Diabase*. Bull. Geol. Soc. Amer., vol. 51, 1940, p. 1059.

CHAPTER VIII.

ERUPTIVE ROCKS—THE UNDER-SATURATED CLASS

(FELDSPATHOIDAL GROUP).

In these rocks the place of alkali-feldspar is partly or wholly taken by feldspathoids—nepheline, leucite, sodalite, hauyne, nosean, cancrinite or analcime. In extreme cases no feldspar is present at all, but in the commoner foyaites and phonolites an alkali-feldspar makes up fifty to seventy per cent. of the rock and feldspathoids twenty to thirty per cent.

In Zirkel's system, rocks with alkali-feldspar and feldspathoid formed Class III.; the deep-seated varieties were called *elæolite*- (or nepheline-) syenite and the lavas phonolite. Rocks with plagioclase and feldspathoid constituted Class V, the deep-seated forms being called *therolith* and the lavas either *tephrite* or *basanite* according to the absence or presence of olivine. In Class VI Zirkel put the *ijolites*, *nephelinites* and other rocks which contain feldspathoids without any feldspar.

Rosenbusch spread the feldspathoidal rocks over four families: the family of nepheline- and leucite-syenites;; the family of shonkinites and *theralites*; the family of *missourites* and *fergusites*; and the family of *ijolites* and *bekinkinites*; and in addition he admitted rocks containing small or moderate quantities of feldspathoids into two other families—the syenites and the *essexites*. Many of Rosenbusch's alkali-syenites contain nepheline or sodalite; indeed sodalite-syenite and analcime-syenite are treated as definite varieties of syenite. Nepheline-monzonite and leucite-monzonite are also described among

the syenites instead of among the nepheline- and leucite-syenites. Similarly the description of the trachytes includes that of many sodalite, nepheline and leucite-bearing varieties. So inconsistent was Rosenbusch's treatment of this group of rocks that he created a subdivision of "phonolitic trachytes" or trachytes containing feldspathoids, and another of "trachytic phonolites" or phonolites holding little or no feldspathoid. The essexite family, too, is defined in such a way that its members may either hold feldspathoids or not.

Most writers have followed Rosenbusch's lead; thus Iddings describes syenites and trachytes which hold small quantities of nepheline; and Harker describes trachytes containing nepheline and sodalite. In Niggli's mineralogical system, the order of syenitic rocks may hold either quartz or feldspathoid. In former editions of Hatch's work the same laxity was permitted, but in the later editions the undersaturated rocks are definitely separated from the others. Even in the Norm classification one finds that the fifth order of the classes Dosalan and Salfemane receives rocks which may hold either a little quartz or a little feldspathoid—usually less than ten per cent. of either, but sometimes more.

In the system of the present writer, as already explained, the presence of any proportion of feldspathoid, however small, is enough to bring the rock into the undersaturated class. The subdivision of the feldspathoidal group of rocks proceeds on similar lines to those followed in the earlier classes, with the exception that, in view of the possibility that some or all of the orthoclase may be replaced by leucite, the usual ratio of orthoclase to anorthite ($\text{Or} : \text{An}$) is replaced by the ratio of orthoclase plus leucite to anorthite ($\text{Or} + \text{Lc} : \text{An}$). The scheme is as follows:—

- | | |
|---|---------------------|
| Group I. $\text{Or} + \text{Lc} > \text{An}$. | (a) Leucite present |
| | (b) Leucite absent |
| Group II. $\text{Or} + \text{Lc} < \text{An}$. | (a) Leucite present |
| | (b) Leucite absent |

Further steps in subdivision take account of the proportion of feldspathoid to feldspar and the colour index (proportion of heavy minerals) of the rock.

The name foyaite, originally applied to the nepheline-syenite of Foya, Portugal, was extended by Rosenbusch to all nepheline-syenites with trachytic texture. It is used here as a general term for all nepheline-syenites.

GEOLOGICAL OCCURRENCE.

With only four striking exceptions, feldspathoidal rocks occur in quite small bodies. The Kola Peninsula, in north Russia, has perhaps the largest body of nepheline rocks, with an area of more than six hundred square miles. The massif of Itatiaya in Brazil is almost equally large but is not yet known in detail. Pilansberg (Pilaan's Mountain) in the western Transvaal holds nearly two hundred square miles of such rocks; and in the south of Greenland two separate bodies of at least fifty square miles each are known. The Kola and Pilansberg masses are interpreted as laccoliths; the structure of the Greenland masses is not properly known. Most of the other occurrences in the world are small stocks, dykes, sills and volcanic plugs, or else they are marginal faciès of granite masses. Feldspathoidal lavas are uncommon and their bulk is insignificant compared to that of rhyolites and basalts, but they have a considerable local importance. For instance, in the Roman and Vesuvian regions of Italy, leucite- and nepheline-bearing lavas are the commonest of rocks; and they have a comparatively large local development in the west of Germany, in East Africa, in Java, and in Wyoming and South Dakota.

Considering the comparative rarity of feldspathoidal rocks, and their small bulk, one is driven to conclude that these rocks have been formed under special conditions from magmas of more usual composition. Many bodies of nepheline rocks pass over quite gradually into syenite and sometimes into granite. R. A. Daly drew attention to the very common association of nepheline

rocks with thick limestone formations, and suggested that the nepheline may have been produced in consequence of a process of desilication of basaltic or granitic magma by reaction with limestone. There is a great deal of field evidence which seems to support Daly's hypothesis. The most striking illustration of the granite-foyaite-limestone association is in the districts of Haliburton and Bancroft in Ontario, where the immensely thick limestone of the Grenville series has been invaded by granitic magma, and the schistose members of the same series have been impregnated with nepheline, or cut by coarse-grained nepheline pegmatites. Other well-known examples of the same association are found at Alnö, Sweden; the Fen district, Norway; Iron Hill, Colorado; and in the district of Sekukuniland, Transvaal.

If nepheline can be formed by reaction between magma and limestone, so without doubt can the other feldspathoids. Sodalite, haüyne, nosean and cancrinite are formed by the addition of a chloride, sulphate or carbonate radicle to the molecule of nepheline. In the case of leucite, there is direct evidence in at least one instance of its formation by the intervention of limestone. H. A. Brouwer has found blocks of limestone in the cone of the andesitic volcano Merapi, in Java, which are cut by veins of leucite-phonolite.

The interesting problem of the origin of feldspathoidal rocks is discussed at length in various papers to which references are given at the end of the chapter.

MINERALOGY AND TEXTURE.

Among eucrystalline rocks the principal feldspathoid is nepheline. When the proportion of nepheline is small the mineral crystallizes late and occupies the interstices between the feldspar crystals, and then it is difficult to detect it without the use of acid. When abundant, nepheline usually crystallizes early, and little crystals of nepheline and sodalite are often enclosed in feldspar

tables in such number as to give a mottled appearance to the cleavage surfaces of the feldspar. In some dyke-foyaïtes and phonolites the insets of nepheline are as large and conspicuous as those of feldspar, and if both have the same flesh-colour the former may be overlooked. When nepheline is present in any quantity in a rock, the first indication that one gets of its presence is generally the appearance of little polygonal pits on the weathered surface of the rock. Intergrowths of orthoclase and nepheline, resembling the micropegmatite of acid rocks, have been observed in some foyaïtes.

Leucite is almost entirely restricted to lavas and fine-grained dyke-rocks; the rock called missourite, which occurs in limited amount in the Highwood Mts. of Montana, is one of the few examples of an eucrystalline rock containing unaltered leucite. In most cases leucite is a mineral of early crystallization. It has been observed during eruptions of Vesuvius that leucite crystals are present in the lava before it has ceased to flow; and when a lava consisting partly of leucite crystals and partly of glass is analyzed, it generally appears that the crop of leucite crystals actually present represents nearly the whole theoretical yield. But in some of the very remarkable glassy lavas of the Leucite Hills in Wyoming, the visible crystals are of diopside and mica and the leucite is retained in the glass. Leucite crystals sometimes transform into aggregates of orthoclase and nepheline or zeolites—the so-called pseudo-leucite—which retain the trapezohedral form of the original crystals. Such pseudomorphs have been found in many foyaïtic and phonolitic rocks, but it is not always certain that the original mineral was leucite. In some cases it is more likely to have been analcime, which crystallizes in the same form as leucite.

Sodalite is present in many foyaïtes and phonolites, and on occasion it may exceed nepheline in quantity. When of early crystallization it forms little rhombic dodecahedrons; when late, it forms very irregular, branching areas that look like *amœbæ*, within larger

pieces of feldspar or nepheline, or within the ground-mass of the rock, which it seems to be in the act of replacing. Sodalite possesses in a high degree the interesting property of fluorescence; when a rock containing sodalite is exposed to ultra-violet radiation in a dark room, the sodalite grains glow with a beautiful golden yellow light. Haüyne and nosean, which are near relations of sodalite, crystallize early and are practically confined to volcanic rocks.

Cancrinite is found especially in foyaitic rocks which cut limestone, a condition of its formation being a high concentration of carbon dioxide in the system. Some cancrinite crystallizes early and may be enclosed in feldspar, but much of it is a product of auto-metamorphism, having been formed at the expense of nepheline at a late stage in the cooling of the magma. The nepheline crystals in these rocks may be reduced to rounded fragments which are completely enveloped by brightly polarising cancrinite. It is important to distinguish between cancrinite and the secondary, scaly mica which is sometimes formed from nepheline. In spite of a superficial resemblance due to their pale colour and high birefringence, the two products are very easily distinguished by the low refractive index of cancrinite and its complete solubility in acids, with effervescence.

Analcime is perhaps commoner than is generally supposed, but it is not always easy to decide whether it is of primary or secondary origin. Some rare kinds of lava carry quite large insets of analcime—in rocks of south Greenland these have been found up to twelve centimetres in diameter—and no adequate reason has been given for supposing that they are not primary. The blairmorite of Alberta is a porphyritic lava which carries over seventy per cent. of analcime. H. S. Washington has shown that crystals of analcime have sometimes been mistakenly described as leucite. On the other hand, analcime is a possible alteration-product of either nepheline or feldspar, and when it occurs interstitially in deep-seated rocks it

may be due to auto-metamorphism. Even leucite can transform into analcime when it is exposed to the action of soda-bearing solutions, and some writers have assumed that the analcime crystals described above are pseudomorphs after leucite. Before this conclusion is accepted, it should rest on something better than assumption.

In no instance has quartz ever been demonstrated in an unaltered nepheline-bearing rock, except in the form of foreign grains which have been picked up by the moving magma. Many cases of this kind have been recorded, and it is generally observed that there has been reaction between the quartz grains and the magma, leading to the production of a soda-feldspar or a zeolite. Leucite, too, is incompatible with quartz under ordinary conditions, but it has been shown that leucite and silica can coexist (in the crucible) above 1170° C. If a potash-rich magma began to crystallize at some such temperature as this, and were then chilled rapidly, we might expect to get a rock consisting of leucite crystals in a highly siliceous glass base. Such lavas have actually been described in Wyoming and in the Roman region, and more recently in Western Australia.

Any kind of feldspar may accompany nepheline or leucite, but on the whole nepheline is more commonly found together with an alkali-feldspar, and leucite with a calcic plagioclase ranging from labradorite to anorthite. Among the nepheline rocks one meets every possible variety of alkali-feldspar, from microcline and orthoclase through soda-orthoclase and every kind of perthitic intergrowth to pure albite. Frequently the crystals of soda-orthoclase or micropertthite are surrounded by mantles of albite. Some curious foyaites of the Transvaal carry large insets of highly potassic microcline in a groundmass which contains only soda feldspar.

Among the dark minerals of feldspathoidal rocks, by far the commonest is a pyroxene ranging in composition from diopside (or hedenbergite) to ægirine. Intermediate members of this series are often described as "ægirine-

augite," but acmite-diopside or soda-diopside is a better description since the mineral is typically non-aluminous. The crystals are commonly zoned, with diopsidic cores and ægirine-rich mantles. The cores of these crystals began their crystallization early, but the ægirine of the mantles formed so late that it is moulded on feldspar and nepheline, or it may be crowded with little enclosures of these minerals. Soda-amphiboles (arfvedsonite, riebeckite and others of doubtful composition and variable properties) are much less common than soda-pyroxenes, but are sometimes formed by transformation of the latter. They are always of late growth and form spongy masses among the other minerals. Common augite or titan-augite and deep brown hornblende are found especially in the plagioclase-bearing rocks, and in these olivine and melilite frequently make their appearance too. Lime-ferric garnets (melanite, schorlomite) are not uncommon, more especially when the rock is intrusive in limestone; and minerals rich in titanium, zirconium and other rare metals have a surprisingly large development in feldspathoidal rocks. Sphene forms prominent wedges, and sometimes skeletal plates which enclose crystals of feldspar, nepheline, etc. Astrophyllite, eudialyte, ænigmatite are also filled with enclosures, and even zircon may crystallize after feldspar and nepheline. Pectolite $\text{HNaCa}_2(\text{SiO}_3)_3$ is an interesting accessory mineral in some nepheline rocks; it indicates the presence of sodium metasilicate in the magma.

Biotite is often present in minor quantity in nepheline rocks. It is an iron-rich variety (lepidomelane), either green or very dark brown in colour. White mica is not usually seen in these rocks, but both muscovite and corundum are present in foyaites in Ontario. Tourmaline has seldom been recorded.

The texture of the eucrystalline feldspathoidal rocks is sometimes granitic, but much more frequently parallel or trachytic, the feldspar crystals having a pronounced tabular habit and lying in more or less parallel position. When

the dark minerals are developed in needles, as ægirine often is, then the texture of the rock may be positively schistose, the rock having all the appearance of a hornblende-schist. To such schistose ægirine-foyaïtes, which are well-developed at Lujaur-Urt in the Kola Peninsula, the name lujaurite has been given. Another textural peculiarity of many foyaïtes is that the dark minerals—especially those rich in soda—crystallize so late as to form spongy masses which are crowded with little enclosures of feldspar, nepheline, etc. This is the so-called poikilitic texture. In some foyaïtes every mineral present except nepheline presents this character.

ROCKS CONTAINING LEUCITE.

The best known example of an eucrystalline rock containing unaltered leucite is the missourite of the Highwood Mts., Montana. This is a coarse-grained, melanocratic rock of dark green colour spotted with white. The principal constituent is diopside, which forms fifty per cent. of the rock. Other dark minerals are olivine, biotite and iron ore, forming a quarter of the rock. Leucite, together with some zeolites formed by its alteration, makes up the remaining quarter. It is partly intergrown with diopside and partly interstitial, having obviously been almost the last substance to crystallize. In a more leucocratic rock from the same district, which has been named fergusite, the leucite has crystallized early and shows its trapezohedral form; but in this case the leucite substance has transformed entirely into pseudoleucite, consisting of grains of nepheline and laths of orthoclase. Between the pseudomorphs the rock consists of diopside, olivine and a little biotite, with apatite and iron ores. In a third rock from the same region leucite has been found partly in the fresh state and partly in the form of pseudoleucite.

A porphyritic rock found at Magnet Cove, Arkansas, holds large trapezohedral pseudomorphs similar to those mentioned above, in a groundmass of nepheline, ortho-

clase, soda-pyroxenes, melanite and biotite. While it is likely that these pseudomorphs are actually pseudoleucite, it should not be forgotten that in the blairmorite of Alberta, which is a rock of very similar composition, the trapezohedral crystals are analcime, not leucite. Another rock which contains rounded to angular bodies which have been regarded as pseudomorphs after leucite is the borolanite of Loch Borolan in north Scotland. This is a dark coloured rock rich in melanite, holding white patches composed of orthoclase and zeolites. When the writer first studied this rock in the laboratory he thought that the white spots were pseudoleucite; but on subsequently examining the rock in the field he was led to conclude that the leucite theory was untenable, and that the rocks had been aggregates of orthoclase and nepheline in the beginning. Whatever the truth may be, it is clear that in all such cases there are other possibilities besides the pseudoleucite one.

Leucite-bearing lavas are generally described as leucite-phonolite when they contain orthoclase; leucite-tephrite when plagioclase; and leucitite when no feldspar is present. If olivine is present in addition to leucite, then the names leucite-basanite (with plagioclase) and leucite-basalt (without feldspar) are used; but the British Petrographic Nomenclature Committee recommended in 1921 that these names should be replaced by olivine-tephrite and olivine-leucitite. The leucite-phonolites are pale-coloured rocks of trachytic appearance, consisting of orthoclase or soda-orthoclase, nepheline and leucite, sometimes with sodalite, nosean or haüyne, the dark minerals being typically soda-diopside and ægirine. Melanite is not uncommonly present too. The leucite crystals in these rocks are angular to rounded but never interstitial.

The italite of the Alban Hills, near Rome, is an exceptional variety of leucitite which carries about ninety per cent. of leucite, with just a little soda-diopside, melanite, biotite and glassy base. It is not really an

independent rock, but probably just the result of a local accumulation of leucite crystals, and a special name is hardly deserved. Such an accumulation of crystals, in the upper part of a dyke, has been observed in the Highwood Mts. of Montana.

Leucitites and leucite-tephrites are mostly dark grey in colour, holding between twenty and fifty per cent. of dark minerals and fifteen to thirty of basic plagioclase (labradorite to anorthite). As in all rocks that carry much plagioclase, the pyroxene is a greenish or brownish augite like that of basalts. Brown hornblende is not common, but olivine is often present and melilite in some cases. When the proportion of dark minerals rises greatly, the crystallization of leucite seems to be delayed. We have seen that in missourite, which consists to the extent of about three-quarters of dark minerals, the leucite crystallized late, partly filling the interstices between the other minerals. So in the rock called madupite, from the Leucite Hills of Wyoming, there are insets of diopside and phlogopite in a base of leucite-glass. Analysis of this rock shows its potential composition to be as follows:—diopside 46, phlogopite 19, leucite 20, nosean 6, accessory 8 per cent.; the rock is therefore the glassy form of a melanocratic leucitite.

ROCKS NOT CONTAINING LEUCITE.

The old name for an eucrystalline nepheline-orthoclase rock is *elæolite*- (or nepheline-) *syenite*; but as the nepheline rocks are actually commoner than the true syenites, and it is absurd to treat the commoner rock as a variety of the less common one, the writer prefers to use the name *foyaite* (from Foya in Portugal where one of the earliest discoveries of a nepheline rock was made) as a generic name for all such rocks.

Far too many specific names have been coined for foyaitic rocks. The only ones that need be mentioned here are *malignite*, a mesotype foyaite; *ijolite*, a rock in

which nepheline has entirely displaced feldspar; and jacupirangite, a melanocratic foyaite or ijolite. For foyaitic lavas two names are sufficient — phonolite for those that contain orthoclase, and nephelinite for those without any feldspar. The nepheline-plagioclase rocks have their own crop of names, of which theralite (for eucrystalline rocks) and tephrite (for lavas) are the best established.

Most foyaitic rocks are *peralkaline*, having soda-diopside or ægirine, less frequently a soda-hornblende, as their dark minerals. Melanite is common near limestone contacts, and eudialyte, astrophyllite, pectolite and other soda-rich minerals are much commoner than they are in any other class of rock. The feldspar is almost always some kind of microperthite, usually with some free albite in addition. The composition of foyaite often falls between the following limits:—alkali-feldspar 50 to 65; nepheline 20 to 30; sodalite 2 to 5; pyroxene, etc., 10 to 20 per cent. The foyaïtes of Serra de Monchique and Cevadaes, in Portugal; of Alnö, Sweden; of Ilimausak, Greenland; of Magnet Cove, Arkansas; of Pilansberg, Franspoort, and Leeuwkraal, South Africa; and of Granitberg, South-West Africa, are some of the major occurrences that fall within these limits of composition.

Among foyaïtes with a larger proportion of dark minerals, the Lujaur type is specially worthy of mention. The name *lujaurite* was given to rocks of Lujaur-Urt, in the Kola Peninsula, which are characterized by an abundance of needles of ægirine in parallel position, giving the rock the appearance and texture of a schist. Eudialyte and other rare minerals are also present in some quantity in these rocks. Rocks identical in every respect with those of Lujaur-Urt were later discovered in Greenland and afterwards in the Transvaal; and in all three localities the lujaurite builds such large masses that it must actually be considered one of the commoner varieties of foyaite. The parallelism of the ægirine needles may be a consequence of crystallization under unequal pressure,

but it is not clear why ægirine should at the same time be more abundant than it is in normal foyaites.

Of rocks in which nepheline is very abundant, the ijolite* type (named from a locality in Finland) is interesting. These rocks consist essentially of nepheline and a sodic pyroxene, with accessory minerals such as cancrinite and melanite, sphene and apatite. Such rocks have definitely been formed in some cases (and probably in all) from a more normal foyaitic magma by assimilation of limestone. Beautiful examples of this type of rock are known at Magnet Cove, Arkansas; the Fen district, Norway; Kuusamo, Finland; and Sekukuniland, Transvaal.

Foyaites of *peraluminous* type have been found especially in Canada. In these rocks the feldspar is mainly albite; a dark brown mica (lepidomelane) is the principal dark mineral, and corundum and muscovite are often present in addition. Similar rocks occur at Miask, in the Ural Mts. *Metaluminous* foyaites, carrying common hornblende and diopside instead of soda-rich varieties, are also known but they are uncommon. The borolanite of Scotland is remarkable for its high content of melanite, which makes up fully a quarter of the rock. The feldspathoids of this rock are altered into zeolites.

The eucrystalline nepheline-plagioclase rocks ($Or < An$) are known as theralite and essexite, two names that have never been clearly distinguished from each other. The original essexite, which takes its name from Essex County, Massachusetts, has been shown to be a product of contact metamorphism, so we prefer to use theralite as a general name for this group. The typical theralite of Duppau, Bohemia, contains a rather calcic feldspar together with interstitial nepheline and orthoclase; the abundant dark minerals are purple augite and brown hornblende, sometimes with the addition of olivine. These rocks may be described as nepheline-bearing dolerites. Some theralites carry a little interstitial analcime and

* Pronounce *eye-yo-lite*.

form passage-facies between theralite and analcime-dolerite. None of these rocks has any quantitative importance.

Of the *effusive* rocks, the phonolites are pale to dark grey rocks of trachytic to basaltic appearance, according to the proportion of dark minerals. They often carry insets of feldspar, less commonly some of nepheline. The groundmass is fine-grained and consists of feldspar laths, short hexagonal prisms of nepheline which give four- and six-sided sections, and needles of ægirine or soda-diopside. Sodalite, haüyne and nosean are often present in small quantity, and melanite is sometimes seen. Good examples of phonolite are known in the Eifel and Kaiserstuhl districts of Germany, the Mittelgebirge of Bohemia, the Roman region of Italy, the Great Rift Valley of Africa, and the Apache Mts. of Texas.

Tinguaite is a variety of phonolite which holds so much ægirine in the form of minute needles that the rock has a greenish colour. It corresponds to the *lujaurite* type among the more deep-seated rocks. These rocks take their name from the Serra de Tingua in Brazil. They occur also in Montana, Texas and Arkansas, and on a large scale as dykes and sheets in Pilansberg, Transvaal.

The nephelinites are dark grey, basaltic-looking rocks in which nepheline is confined to the groundmass and often difficult to find without staining. The chief dark mineral is augite, not ægirine, and olivine and melilite are often present too. The nephelinite of the Katzenbückel is olivine-free; it has large crystals of augite and some of nosean in a groundmass of augite grains, nepheline, and a little feldspar. Nephelinites of the Auvergne and the Bohemian Mittelgebirge are also olivine-free; those of the Kaiserstuhl, the Eifel, and the Bearpaw Mts. of Montana are olivine-nephelinite or nepheline-basalt.

Nepheline-tephrites and basanites are plagioclase-bearing lavas of basaltic appearance, the former without and

the latter with olivine. Rocks of this type are known in the Canary Islands, in the Elkhead Mts. of Colorado, and near Dunedin, New Zealand.

SUGGESTIONS FOR READING.

- F. D. ADAMS and A. E. BARLOW, *Geology of the Haliburton and Bancroft Areas*. Canada, Dept. of Mines, Mem. no. 6, 1910.
- R. A. DALY, *Igneous Rocks and the Depths of the Earth*. 1933, chap. 21.
- S. J. SHAND, *Eruptive Rocks*, 1943, chap. 18.
- S. J. SHAND, *The Nepheline Rocks of Sekukuniland*. Trans. Geol. Soc. S. Africa, vol. 24, 1921, p. 111.
- S. J. SHAND, *The Present Status of Daly's Hypothesis of the Alkaline Rocks*. Amer. Jour. Sci., vol. 243—A, 1945, p. 495.
- S. J. SHAND, *On the Staining of Feldspathoids*. Amer. Mineralogist, vol. 24, 1939, p. 508.

CHAPTER IX.

SEDIMENTARY ROCKS.

(1) SEDIMENTARY ROCKS IN THE FIELD.

The character by which a sedimentary rock is immediately recognized in the field is its arrangement in layers which we call beds or strata, or if they are very thin, laminæ. Some very coarse-grained deposits are almost unstratified, but traces of a rude bedding are seldom entirely absent. The stronger beds are commonly from an inch or two up to several feet in thickness, and they are separated by bedding-planes which open easily to the tap of the hammer; indeed, the more strongly marked bedding-planes often gape at the outcrop. Between the stronger bedding-planes there are generally many other surfaces of poor cohesion along which the rock can be split into thin sheets which, in a very fine-grained rock, may be as thin as sheets of paper. These are the laminæ, which bear the same relation to the beds as the pages do to the volumes on a library shelf.

The presence of a strong bedding-plane generally marks a slight interruption in the deposition of the sediment, during which the surface was smoothed off and the grains packed closely together, while a thin skin of the smallest grains formed on top. The stronger beds of a sandstone series are often separated by thin partings of clay. This feature may be obscured, in a natural outcrop, by the washing out of the clay particles, but in an artificial cutting the partings will be clearly seen. In-

stead of a clay film there may be one of tiny mica scales, all lying in parallel position. The bedding-planes of a sandstone often glitter brightly in sunshine owing to such a film of mica scales. All such interruptions and changes of texture cause the rocks to split easily along the bedding-planes, either naturally, in consequence of change of temperature, or else under the hammer.

The lamination of fine-grained rocks may result from the alternation of more granular with more colloidal layers, or from the parallelism of flat grains and scales, or it may be a consequence of movement under compression. The very perfect cleavage that is shown by true slates is a consequence of the tremendous pressure developed during mountain-building movements, when plastic flow is set up in the soft rock at a high angle to the direction of pressure. The cleavage of the slate is superimposed upon the lamination of the original shale, and traces of the lamination may still be detected as wavy bands of slightly different colour running across the cleavage faces of the slate.

The bedding of sedimentary rocks is sometimes simulated by the flow-bands of a lava sheet, and the parallel texture of a gneissic granite is very similar to the lamination of a sandstone; but a confusion of these structures is hardly possible except to a complete novice. Many highly metamorphic rocks are composed of parallel bands of darker and lighter colour, which from a distance look exactly like the beds of a sedimentary formation. Such rocks have in fact been formed by the metamorphism of sedimentary beds, or by the injection of sheets of granite along the bedding-planes of a sedimentary series, so the structure has a sedimentary origin in any case.

Many sandstones and banded shales show a type of lamination that is clearly due to rapid alternations of coarser and finer material. There may be, for instance, a succession of coarse sand, fine sand and sandy clay, in bands only a few millimetres thick, repeated with great regularity through a formation many feet or yards in

thickness. There is little doubt that this type of lamination or "graded bedding" preserves a record of seasonal changes during the accumulation of the deposit; either changes in the direction of ocean currents in response to seasonal changes of wind-direction, or else alternations of wet and dry or warm and cold seasons. It is possible in such a case, by counting the number of repetitions in a given thickness of rock, to find the time required for the accumulation of the whole formation, just as one finds the age of a tree by counting the annual rings. The most perfect examples of rhythmic lamination are formed under glacial waters.

Lamination is generally parallel to bedding, but in the case of current-bedding (false-bedding) the laminæ may be inclined as much as twenty or thirty degrees to the stronger dividing-planes, and the laminæ may have different inclinations in different beds. This condition arises when a sandbank (under water) or a sand-dune (on land) travels forward with a current of water or of air. Grains of sand are carried over the top of the bank and dropped down the face, to settle on the sloping front. The laminæ, which are the real planes of accumulation, are therefore inclined to the horizontal, and what we call the bedding-planes of the sandstone are intervals of interrupted accumulation during which the upper edges of the laminæ were planed down by the current before the next layer was deposited. The presence of current-bedding is a sure indication of shallow-water or sub-aerial conditions of deposition.

In addition to planes of bedding and of lamination, sedimentary rocks are cut by joints just as igneous rocks are. There are generally two but sometimes three or more directions of jointing, which may be either perpendicular or inclined to the bedding-planes. In tilted beds which are strongly jointed but free from lamination, it may be quite difficult to distinguish joints from bedding-planes, especially when the exposure is a small one such as a shallow prospecting pit or adit.

The stronger bedding-planes of sandstone are often crossed by ripple-marks or systems of parallel ridges and furrows exactly similar to those seen on the seashore or on a sandy river-bed. In most cases the wave-length, or the distance from one ridge to the next, is only a few centimetres; but beneath a rapid current ridges may be formed at intervals of several feet. Either air-currents or water-currents may produce ripples on loose sediment; and even the passage of waves across the surface of a stationary sheet of water sets up oscillations which are transmitted downwards and throw the surface of the underlying sand into ripples. The ripples caused by oscillation can be distinguished from those caused by currents by their symmetry; oscillation-ripples having the same angle of slope on each side while current-ripples have a steep slope facing downstream and a gentler slope upstream. The presence of symmetrical ripples therefore indicates the absence of currents. A complex type of oscillation may give rise to two or three series of intersecting ripples, between which the troughs are reduced to little polygonal pits.

The crests of ripples are normally sharp and the troughs rounded, so it is possible by observation of ripple-marks to tell whether a strongly tilted sedimentary series has been overfolded or not. The same information may be gained by studying the succession of the layers in cases where there is graded bedding.

Ripples produced by air-currents on dry sand differ in a characteristic way from those formed by running water. If the wave-length, or distance from crest to crest, is divided by the amplitude, or height of the crest above the trough, the result is what has been called the "ripple-mark index." E. M. Kindle claims that water-formed ripples have an index of 4 to 10, wind-formed ripples from 20 to 50 or more. If this could be established it would be a valuable means of learning the conditions under which a ripple-marked sediment was laid down, but data published by other writers do not always agree with

Kindle's figures. W. F. Hume found, on a sand dune at Ismailia, wind ripples with an index of 11 to 23, the average being 16.6. Ripples left by the receding Nile at Sakhara gave the values 18.3 and 17.9 on different days.

Fine mud, held in suspension in fresh water, takes a long time to settle; but the addition of an electrolyte such as common salt hastens the settling process. E. M. Kindle has shown experimentally that if particles of different kinds, such as clay, chalk and sand, are added to fresh water in a tank, the separation of the different kinds of grains in settling is imperfect. If the same materials are added to salt water the separation is nearly complete and the layers are sharply contrasted. This is held to justify the statement that marine sedimentation tends to give sharply contrasted beds, such as pure sands, pure shales and pure limestones; while sedimentation under fresh water gives beds with little contrast, such as sandy shales and argillaceous sandstones, with impure limestones. It is likely, however, that the lack of contrast observed in many fresh-water deposits is due to the flocculating action of organic colloids and iron hydroxide on suspended sediment. It has been shown that these bodies are electro-positive towards the water in which they are suspended, while clay is electro-negative, consequently the addition of the former to the latter causes the particles to collect together in flocks which sink rapidly and so give rise to an ungraded or poorly graded deposit. The presence of cavities or sand-casts having the characteristic hopper-shape of salt crystals is good evidence of deposition under salt water.

Deposits formed under tropical climatic conditions show a very thorough decomposition of feldspar and other anhydrous silicates, with production of hydroxides and hydrous silicates (clay-silicates). Vegetable matter is often enclosed in such deposits, and this gives them a dark colour and prevents the complete oxidation of the iron. Pyritic black shales and coal seams are common, although it cannot be said that all such rocks were necessarily formed under tropical conditions.

Desert deposits have some very characteristic features. The minerals are very fresh, and the grains may be coated with thin films of red iron-oxide. Sand grains are well rounded and polished, but coarser fragments which are too heavy to be rolled along by the wind are angular, and among the larger pebbles some may show the curious "dreikanter" form which is produced by the action of the sand-blast. Sorting is poor, coarser and finer stuff being intermingled to a greater extent than in water-formed deposits, and stratification is also poor, although false-bedding may be well marked. Mud deposits show sun-cracks and casts of salt crystals; and the former presence of salt-pans may be indicated by beds of rock salt or gypsum.

The material called "loess," which covers large areas in central Asia and China, is a light dust deposit consisting of fresh and mostly angular grains of feldspar, quartz, and other common rock-forming minerals. It is poorly stratified, except where it has been rearranged by water, and the only fossils found in it are snail shells and the roots of plants. Loess is believed to be dust carried by wind from the deserts and deposited on the grasslands, where it was trapped and bound together by vegetation.

(2) THE COMPOSITION OF SEDIMENTARY ROCKS.

The units of the coarser sediments are not so much mineral grains as lumps of pre-existing rocks, and of these it is not necessary to say anything here except that it is chiefly the rocks that are most resistant to weathering and disintegration that are preserved as boulders in the sedimentary deposits. Thus boulders of granite and vein-quartz are common; boulders of dolerite or basalt or any other dark-coloured igneous rock are quite uncommon.

The smaller grains of the sedimentary rocks are fragments of single minerals. These may be arranged at once in two classes. Some of them have been derived directly from pre-existing rocks without undergoing any chemical change; they are crystalline, although they may have lost

THE STUDY OF ROCKS

race of their crystalline form. The minerals of the r class are secondary products formed by the oxidation, hydration and carbonation of primary silicates; they are gelatinous, spongy or fibrous, except when they are appreciably soluble in water and have been recrystallized in solution. Somebody has coined for these two classes of products the expressive terms rock flour and rock rot. The principal minerals of rock flour are quartz, feldspar, soda-rich plagioclase, muscovite, augite and hornblende, garnets, tourmaline, epidote, rutile, ilmenite, apatite and zircon; with many others in small quantity. The chief minerals of rock rot are the hydrous silicates, the hydro-micas, the chlorites, glauconite, limonite, and chalcedony; together with recrystallized carbonates (calcite, aragonite, dolomite, etc.), sulphates (gypsum, anhydrite), chlorides (rock salt) and sulphides (pyrite, pyrrhotite and marcasite). A full account will be given here of such minerals as have already been mentioned in this book:

The *clay-silicates* are hydrous silicates of aluminium, usually containing some magnesium, iron, calcium, sodium or potassium in addition. The study of these minerals formerly presented great difficulties, for their microcrystalline to colloidal character is unsuited to microscopic study, and the proportions of the various elements, indicated by chemical analysis, showed wide variation. Since the application of X-rays to the study of crystal structure, most of these difficulties have disappeared. By the combination of microscopic evidence with chemical analysis, thermal analysis, and X-ray data it has been possible to recognize a few simple species which form the bulk of most clays. Of these species, kaolinite and montmorillonite are the commonest, kaolinite being the chief constituent of the china-clays and montmorillonite that of the bentonitic clays. Kaolinite has the simple composition $2\text{H}_2\text{O}, \text{Al}_2\text{O}_3, 2\text{SiO}_2$; it is formed by the weathering of feldspathic rocks such as granite. Montmorillonite is the name of a solid-solution

series which begins with an aluminous member (pyrophyllite) but nearly always contains magnesia and lime in addition. A typical formula is $6\text{H}_2\text{O}, 2\text{MgO}, 5\text{Al}_2\text{O}_3, 24\text{SiO}_2$. The substitution of ferric oxide for alumina gives nontronite or chloropal. The clays of the montmorillonite series are formed by the weathering of the ferromagnesian minerals in rocks, and by alteration of volcanic glass, ashes, and tuff.

Other clay-silicates of definite composition, such as dickite and halloysite, seem to be formed by hydrothermal action, not by weathering, and play a minor part in the composition of sedimentary rocks.

Minerals of the *zeolite* group were formerly supposed to play a large part in the composition of clays, but modern studies do not support this view. However it has been shown that a zeolitic mineral may be an intermediate product in the formation of montmorillonite.

The *hydro-micas* are a group of minutely scaly or cryptocrystalline minerals which are probably not different in any essential respect from ordinary muscovite. Some of them hold more water and less potash than is indicated by the usual formula of muscovite. The names sericite, margarodite and pinite are used for such secondary micas.

The *chlorites* are green minerals with a micaceous cleavage; they are hydrous or acid silicates of magnesia, ferrous iron and alumina, and they are formed from the biotite and other ferromagnesian minerals of igneous rocks. The formula of clinocllore is $4\text{H}_2\text{O}, 5(\text{Mg}, \text{Fe})\text{O}, \text{Al}_2\text{O}_3, 3\text{SiO}_2$. Chamosite is a chlorite in which ferrous oxide displaces most of the magnesia. All chlorites yield water on heating, and the vermicularite variety swells up and forms worm-like threads.

Glauconite is a green, earthy mineral resembling some chlorite. It is a hydrous silicate of aluminium, iron and potash, with more or less magnesia, but analyses differ much among themselves owing to the difficulty of obtaining pure material. Glauconite forms rounded grains and

aggregates in many sandstones, and also replaces foraminifera and other organisms in chalk. It is only found in marine sediments such as the Greensand of the Cretaceous system.

Serpentine is another greenish mineral, this time a hydrous silicate of magnesia and iron without any alumina. The formula is $2\text{H}_2\text{O}_3(\text{Mg}, \text{Fe})\text{O}_2\text{SiO}_2$. Serpentine is largely formed from olivine but also from hornblende and hypersthene.

Limonite is the ultimate decomposition product of all iron compounds. It is a brown, earthy or fibrous material with the composition $2\text{Fe}_2\text{O}_3, 3\text{H}_2\text{O}$.

Diaspore and *gibbsite* are hydroxides of aluminium; the former is $\text{Al}_2\text{O}_3, \text{H}_2\text{O}$, the latter $\text{Al}_2\text{O}_3, 3\text{H}_2\text{O}$. Both have a scaly habit.

Chalcedony is a waxy form of silica, having the hardness and density of quartz but a minutely fibrous structure which becomes apparent when the nicols are crossed. *Opal* is hydrous silica in the form of a structureless jelly or glass. When strongly coloured by iron oxides, both chalcedony and opal pass into the semi-opaque form of *jasper*.

Calcite and *aragonite* are dimorphous forms of calcium carbonate. Both forms occur in sea-shells, but calcite is the more stable form under atmospheric conditions, and in limestones formed of shells the aragonite soon transforms into calcite, with an increase of volume. Calcium carbonate deposited by hot springs is generally in the form of aragonite, with a fibrous habit. In presence of solutions containing magnesium chloride calcite slowly transforms into *dolomite*, $\text{CaMg}(\text{CO}_3)_2$. These two minerals resemble each other rather closely but can be distinguished by treatment with ferric chloride, which stains calcite brown, or by Lemberg's solution (aluminium chloride and logwood) which stains calcite but leaves dolomite unaffected. *Siderite* (ferrous carbonate) is generally indicated by the strong brown colour which it develops by oxidation.

Among the sulphates, *gypsum* is important. It is the compound, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, and it forms highly characteristic monoclinic crystals and arrow-head twins, with perfect cleavage parallel to the second pinacoid. Crystals of gypsum that have grown in salt-pans are often rounded and button-like. As a rock, gypsum occurs in beds with a granular to fibrous structure. *Anhydrite* is the water-free form of calcium sulphate; it forms rhombic crystals which have three directions of good cleavage intersecting at right angles. In contact with fresh water anhydrite transforms into gypsum; this involves an increase of 62 per cent. in the volume of the mineral.

Rock salt forms thick beds among the deposits of arid regions; it is typically associated with anhydrite or gypsum. Skeleton cubes of salt grow in mud and may later be leached out, leaving moulds and casts.

Pyrite (FeS_2), *pyrrhotite* (Fe_3S_4) and *marcasite*, the rhombic modification of iron sulphide, form nodules in many sandstones, limestone and shales, and sometimes replace shells.

(3) THE CLASSIFICATION OF SEDIMENTARY ROCKS.

There are no such pronounced differences of opinion regarding the classification of sedimentary rocks as we have met in our discussion of the eruptive group. There is nothing mysterious about the origin of sedimentary rocks; we can see them forming before our eyes and observe how one type of sediment passes either vertically or laterally into another type. A rock of mixed parentage is easily recognized as such, so there has been no need for students of sedimentary rocks to coin new names in order to cover up their ignorance. In short, everybody who has ever attempted to classify sedimentary rocks has recognized the three fundamental classes which we may call rock residues, organic residues, and residues from solution. These classes cannot be held sharply apart, for rock detritus is often mixed with organic detritus, and both may be cemented together by material

deposited from solution; thus we have sandy limestones, gypseous sandstones and salt clays; but for all that the three classes are so fundamentally different that one must separate them as far as possible.

The class of rock residues is always subdivided according to the size of the constituent grains, with the mineralogical composition as a subordinate factor. The organic residues and the residues from solution are subdivided mainly on the basis of chemical composition.

We have no new classification to offer here; the most that we shall attempt to do is to effect some small rearrangement of the groups. The description of the sedimentary rocks in the next four chapters will be based on the following arrangement:—

Class I. **Organic Residues.**

- (a) Limestone and dolomite.
- (b) Guano, phosphorite and bone-breccia.
- (c) Diatomaceous and radiolarian earths.
- (d) Peat, coal and oil-shale.

Class II. **Residues from Solution.**

- (a) Calc-sinter and oolite.
- (b) Ironstone.
- (c) Siliceous sinter, chert, jasper.
- (d) Anhydrite and gypsum.
- (e) Rock salt and other salts.

Class III. **Crystalline Rock-Residues.**

- (a) Breccia and tillite.
- (b) Agglomerate and tuff.
- (c) Conglomerate.
- (d) Grit, arkose and greywacke.
- (e) Sandstone and quartzite.
- (f) Siltstone and loess.

Class IV. **Cryptocrystalline and Colloidal Rock-Residues.**

Clay, shale and slate.

IMPORTANT WORKS OF REFERENCE.

- L. CAYEUX, *L'Etude Petrographique des Roches Sédimentaires*
- H. B. MILNER, *Sedimentary Petrography* (London, T. Murby & Co.).
- W. H. TWENHOFEL, *Treatise on Sedimentation* (Baltimore, 1932).
- W. C. KRUMBEIN and F. J. PETTIJOHN, *Manual of Sedimentary Petrography* (Appleton, 1938).
- F. W. CLARKE, *Data of Geochemistry*, chapters XII., XIII. (U.S. Geol. Survey, Bulletin 770).

SUGGESTIONS FOR READING.

- J. H. MARR, *Deposition of the Sedimentary Rocks* (Cambridge Univ. Press).
- E. M. KINDLE, *Recent and Fossil Ripple-Mark* (Dept. of Mines, Canada; Museum Bulletin no. 25, 1917).
- P. G. H. BOSWELL, *The Action of Colloids in Precipitating Fine-grained Sediments*. Geol. Mag., 1930, p. 371.
- W. H. TWENHOFEL, *Principles of Sedimentation* (McGraw-Hill Co., 1939).
- C. S. ROSS and P. F. KERR, *The Kaolin Minerals*. U.S. Geol. Survey, Prof. Paper 165—E, 1931.
- C. S. ROSS, *Clays and Soils in Relation to Geologic Processes*. Jour. Washington Acad. Sci., vol. 33, 1943.

CHAPTER X.

SEDIMENTARY ROCKS.

CLASS I—ORGANIC RESIDUES.

(a) LIMESTONE AND DOLOMITE.

These rocks are composed largely or entirely of the shells or skeletons of marine — and to a much smaller extent of fresh water—animals and plants. With this organic material a certain amount of sand or silt may be mixed.

The chief organisms that have contributed their shells and skeletons to the formation of limestone are calcareous algæ, foraminifera, corals, crinoids, polyzoa, brachiopods, lamellibranchs and gastropods; with smaller contributions from the echinoids, cephalopods, pteropods, trilobites, ostracods and sponges. The shells of these organisms are mainly composed of calcium carbonate, which may be either in the rhombohedral form (calcite) or the rhombic form (aragonite). But although calcium carbonate predominates, it is important to recognize that many other constituents are present in smaller amounts, and consequently that (quite apart from accidental admixture of sand and mud) a shell-limestone is by no means always a pure deposit of calcium carbonate. The principal associated substances in shells are magnesium carbonate, silica, and calcium phosphate. A most useful study of the chemical composition of the shells of marine invertebrates has been made by F. W. Clarke and W. C. Wheeler, whose findings are summarized here.

Calcareous algæ, which play a large part in the structure of many so-called "coral reefs," are among the

most highly magnesian of all the organisms studied, the analyses yielding from 11 to 25 per cent. of magnesium carbonate. In foraminifera the proportion of magnesium carbonate ranges from 2 to 11 per cent., the highest values being given by shells from shallow, warm waters. The madreporarian corals were found to be almost purely calcareous, but the alcyonarian corals gave from 6 to nearly 17 per cent. of magnesium carbonate, up to 8 per cent. of calcium phosphate, and up to 5 per cent. of calcium sulphate. As in the case of the foraminifera, the corals of warm, shallow seas are the richest in magnesia. The analyses of crinoid fragments gave from 8 to 14 per cent. of magnesium carbonate, and echinoderms gave similar results with the addition of a little calcium phosphate and calcium sulphate. The shells of bryozoa and brachiopods are for the greater part purely calcareous, but some brachiopods make their shells almost entirely of calcium phosphate instead of the carbonate. Lamellibranchs, gastropods and cephalopods have shells of calcium carbonate with very little impurity of any kind. The recent crustacea (crabs, shrimps, lobsters, etc.) form shells of very variable composition, the analyses showing from 5 to 15 per cent. of magnesium carbonate and up to 25 per cent., exceptionally even more, of calcium phosphate.

In general, owing to the isomorphism of calcite and dolomite, it is the shells formed of calcite that show a large content of magnesia, the aragonite shells being almost pure. In addition to the substances mentioned above there may be a contribution of silica from siliceous organisms (algæ, radiolaria, sponges); and it is obvious that accumulations of shell and coral fragments on the sea-floor are likely to be mixed up with more or less sand or silt. Thus many shell-limestones hold small or moderate quantities of silica, alumina and compounds of iron, for instance glauconite.

Some shells disintegrate rapidly after the death of their tenants. This is caused largely by wave-action;

but it is also due to the work of scavenging fishes, which crush the shells to secure their contents, and in part it is simply a consequence of the decay of the connecting tissue which binds the valves or plates of the shell together. Consequently most limestones consist of a relatively small number of entire shells which are embedded in a matrix of shell fragments and calcareous mud. Owing to the appreciable solubility of calcium carbonate in water, such a mixture quickly becomes cemented together. Calcite is more stable at ordinary temperatures than aragonite, so there is a tendency for those shells that are formed of aragonite to be dissolved and for the material to be redeposited as crystals of calcite. It is perhaps for this reason that animals such as the cephalopods, which build their shells of aragonite, are poorly represented in limestones.

The conversion of aragonite into calcite brings about other effects besides cementation of the mass. The specific gravity of aragonite is 2.94, that of calcite 2.72, so the transformation is accompanied by an increase in the volume of the limestone. This expansion must set up strains in the rock which not only hasten the disintegration of the shells but sometimes cause minute faulting and puckering or brecciation of the layers of limestone. If recrystallization affects the calcitic as well as the aragonitic shells, then all trace of shelly structure is eventually lost and the rock becomes a crystalline limestone or marble, which is strictly a metamorphic rock.

Under the microscope some relics of organic structure are generally recognizable in limestones. Tests of foraminifera, joints of crinoids, spines of sea-urchins, and sponge spicules are easily identified; and larger structures can be made out on the hand specimen, especially on weathered surfaces. The larger fragments are embedded in a fine-grained calcareous matrix which may hold some admixed sand grains. In advanced recrystallization the whole rock may consist of interlocking crystals of calcite, with quartz, pyrites and apatite as common accessory minerals.

If the water beneath which the limestone accumulated was saturated with calcium carbonate, then each fragment of shell or grain of sand may be coated with a layer of calcite or aragonite deposited from solution. Thus there is a transition from purely shelly limestones to the calcareous sinters, which are wholly deposits from water.

Although most limestone is formed under water, it has been shown that shell fragments may be carried inland by wind and deposited at a distance from the sea. While the deposit is still loose it may be mixed with snail shells and bones of land animals, which afford proof that consolidation took place above sea-level. These wind-borne limestones, which are known in India, north Egypt, and South Africa, generally show pronounced false-bedding, just as wind-borne sandstones do, and they are contaminated with sand and silicate grains. At Mariut, west of Alexandria, the wind-blown limestone is oolitic.

Most shell limestones must, as we have seen, contain a little magnesium carbonate. When this constituent is present in notable quantity there is a transition through the magnesian limestones (which are often loosely called dolomite) to true dolomite, which has the definite formula $\text{CaMg}(\text{CO}_3)_2$, corresponding to calcium carbonate 54.3 per cent., magnesium carbonate 45.7 per cent. The occurrence of moderately magnesian limestones requires no special explanation, but the highly magnesian limestones and dolomites can not be accounted for by simple accumulation of shells. It has been shown that massive coral rock is often highly magnesian, although the cups of living corals have little magnesia in their composition. Deep borings on the atoll of Funafuti showed that the proportion of magnesium carbonate increased from four per cent. near the surface to over forty per cent. at a depth of 1,100 feet, although the rate of increase was irregular and sometimes negative. It is clear from these results that there must be some process by which limestone can be enriched with magnesia in nature. This

might happen in consequence of the leaching-out of calcium carbonate from a moderately magnesian limestone, leaving the residue richer in magnesia; or there may be an exchange of bases between the molecules of calcium carbonate in the limestone and those of magnesium chloride in sea-water. The cavernous structure of many dolomites is consistent with the idea of their origin by leaching and replacement. By a similar process, calcite may be replaced by ferrous carbonate (siderite), giving rise to an ironstone.

During the dolomitization of a shelly limestone all trace of organic structure is usually lost, unless the fossils were silicified before dolomitization set in. Strictly speaking, dolomite, like marble, is a metamorphic rock, but for the purpose of description it is better to retain it among the sediments. Under the microscope dolomite may be distinguished from calcite by a higher degree of idiomorphism, the dolomite grains showing rhombohedral outlines while calcite grains are irregular. Polysynthetic twinning lamellæ are often observed in calcite, seldom in dolomite, and the twinning planes are different, being (0112) in calcite and (0221) in dolomite. A conclusive test is given by the action of Lemberg's reagent or a solution of ferric chloride, to both of which dolomite is inert.

(b) GUANO, PHOSPHORITE AND BONE-BRECCIA.

Guano consists largely of the droppings of seabirds, mixed with the remains of dead birds and fishes. This material is rich in lime, phosphorus, carbon and nitrogen, and as it decomposes it gradually loses volatile matter and forms a coherent, powdery deposit consisting of phosphates, urates and oxalates of lime, magnesia and ammonia. When this deposit is formed on a coral island, as it very often is, then the soluble ammonium salts are carried down by rain water into the crevices of the coral-limestone, where a reaction takes place, giving calcium phosphate and liberating ammonia. It has been

found that coral rock has been converted in this way into phosphorite down to depths of fifty feet and more. The phosphorite of Christmas Island is a white, porous, chalk-like material containing bones of birds. It is largely amorphous, with a porcelain-like appearance under the microscope; but in places solution and redeposition of the phosphate has produced crusts and agate-like layers of a fibrous, crystalline phosphate, probably the mineral collophane, $\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{H}_2\text{O}$.

If the underlying rock is aluminous instead of calcareous, then phosphates of iron and alumina are formed, as on Clipperton atoll, where trachyte has been phosphatized.

Phosphorite is also found interstratified with shales and limestones of marine origin. The beds are thin and irregular but often continuous over large areas; they seem to represent replacements of limestone by phosphates derived from organisms decomposing on the sea-floor. They might also be accounted for by leaching-out of calcium carbonate from a moderately phosphatic shell-limestone. In the Permian rocks of the western states of America beds of phosphorite from one to five feet thick have been traced over an area of 175,000 square miles. The rock is often oolitic and is interbedded with marine shales and limestones.

The term bone-breccia is self-explanatory. Accumulations of animal remains, cemented by lime or a fine red earth, are often found in caves and other favourable spots which have been inhabited for a long time by wild animals. Bones are rich in calcium phosphate, so bone-breccias are occasionally worked as sources of phosphatic manures. They have some archæological and palæontological importance, but geologically they are of little account.

(c) DIATOMACEOUS AND RADIOLARIAN EARTHS.

Siliceous shells are not so common as those composed of lime, but they sometimes form deposits of appreciable

size. The principal siliceous organisms are radiolaria, diatoms and sponges. Diatomaceous earths (diatomite, kieselguhr) are known in Tertiary formations in many lands. The kieselguhr of Hanover occurs in lenses thirty feet thick, and the deposits in the Miocene beds of Maryland are even thicker. Deposits a hundred to two hundred feet thick are reported in Nevada. Structurally, these deposits consist of aggregates of minute tests of diatoms, radiolaria and foraminifera, only a few thousandths of a millimetre in diameter, often mixed with sponge spicules and mineral grains. Chemically they consist of opaline silica with calcium carbonate and other impurities. Beds of chert often contain shells of radiolaria, and it is sometimes assumed that chert is an altered radiolarian earth, transformed by solution and redeposition of silica.

(d) PEAT, COAL AND OIL-SHALE.

These rocks represent various stages in the decomposition of vegetable tissues. The differences between one coal and another are explained not only by different stages of decomposition but also by differences in the nature of the vegetable matter of which they were formed.

Peat is a spongy, fibrous material, easily cut and easily ignited when dry. It is brown to black in colour and is recognizable at sight as a compacted mass of plant debris, mixed with more or less of earthy matter.

Lignite or brown coal is harder and more compact than peat and is no longer spongy. Fragments of bark or leaves may be recognized, but the bulk of the coal shows no distinct structure in the hand-specimen although a cellular texture is recognizable in thin sections. The fracture is very irregular and most lignite crumbles easily when dry.

Humic coal (common coal) is a still more compact and distinctly stratified mass of "mummified" vegetable fragments. The principal tissues which constitute coal,

and which can be recognized in specially prepared and treated thin sections, are woody fibres, carbonized wood, bark, leaf cuticle, spore-cases and seeds. Humic coal is usually built up of alternating layers of bright, glistening coal and of dull, fibrous coal. The dull layers consist largely of woody matter, and hold most of the "ash" or inorganic constituents of the coal; the bright layers contain more moisture and volatile matter and show spore-cases under the microscope. The "ash" of coal is partly just admixed silt but some of it is mineral matter that was incorporated in the plant tissues. Some plants incorporate silica, others alumina and others lime; and the content of mineral matter is different in different parts of the plant. Fluorine is often present, probably in the form of calcium fluoride.

Coal seems to have accumulated under shallow, fresh or brackish water, in association with sands and clays. The floor of a coal-seam is frequently a very siliceous clay, though other kinds of floor are also possible; the roof is usually shale or sandstone. Single seams may be more than a hundred feet thick, but thick seams are often interrupted by partings of clay or sandstone, or lenses of limestone, and they are less pure than thinner seams.

Cannel coal is a dull black, lustreless coal which does not soil the fingers, breaks with a conchoidal fracture, and is readily ignited, burning with a smoky flame like a candle (hence the name candle-coal). It is believed to have been formed from a gelatinous or slimy mass of spores and other decomposing tissues, including even animal remains, which accumulated under water. Woody tissue seems to be entirely absent.

Anthracite is a shiny black coal which does not soil the fingers. It is nearly free from volatile hydrocarbons, consequently it is difficult to ignite and burns with a very feeble flame. As it contains over ninety per cent. of carbons it gives great heat in burning. Traces of cellular structure can be detected in anthracite by etching a

polished surface with strong oxidizing agents or with a blowpipe flame.

Torbanite and other oil-shales differ from coal by having more hydrogen and a good deal more mineral matter in their composition; on distillation they do not form coke but instead leave a residue of burnt shale. In appearance the richer oil-shales have a woody or leathery look; they can be cut with a knife, and the shavings will ignite when a match is applied to them. The colour is brown to black, the streak brown. The combustible matter or "kerogen," which yields petroleum when distilled, occurs as minute yellow globules or discs a few thousandths of an inch in diameter; these are set in a dark, shaly matrix. According to some workers the yellow bodies are algæ; according to others, spores; while another view is that they are resin fragments shaped by attrition and compression.

SUGGESTIONS FOR READING.

- H. C. SORBY, *The Structure and Origin of Limestones*. Quart. Jour. Geol. Soc., 1879, p. 56.
- J. W. EVANS, *On Mechanically formed Limestones*. Quart. Jour. Geol. Soc., 1900, p. 561.
- L. OWEN, *The Phosphate Deposits of Ocean Island*, Quart. Jour. Geol. Soc., 1923, p. 1.
- M. C. STOPES and R. V. WHEELER, *Monograph on the Constitution of Coal*. H.M. Stationery Office, 1918.
- W. H. TWENHOFEL, *Treatise on Sedimentation*, 1932, chap. 5.
- J. V. LEWIS, *Evolution of the Mineral Coals*. Economic Geology, 1934.
- M. A. HOWE, *The Geological Importance of the Lime-Secreting Algæ*. U.S. Geol. Survey, Prof. Paper, 170—E, 1931.
- G. R. MANSFIELD, *Some Problems of the Rocky Mountain Phosphate Field*. Economic Geology, vol. 26, 1931.
- F. W. CLARKE and W. C. WHEELER, *The Inorganic Constituents of Marine Invertebrates*. U.S. Geol. Survey, Prof. Paper, 102, 1917.

CHAPTER XI.

SEDIMENTARY ROCKS.

CLASS II—RESIDUES FROM SOLUTION.

(a) CALC-SINTER AND OOLITE.

Calcium carbonate is held in solution in water in the form of the bicarbonate $\text{CaH}_2(\text{CO}_3)_2$; and anything which robs the solution of carbon dioxide will cause the normal carbonate to be precipitated as calcite or aragonite. The solubility of calcium carbonate in water depends, then, not only on the temperature of the water but also on the concentration of carbon dioxide. J. Johnston and E. D. Williamson have shown that water at 16°C ., containing only 2 parts in ten million of carbon dioxide, will dissolve 45 parts per million of calcium carbonate. With nine parts of carbon dioxide in ten million, the amount of calcium carbonate dissolved is 75 parts per million. On the other hand, with constant (atmospheric) concentration of carbon dioxide, the solubility of the carbonate decreases from 81 parts at 0°C . to 52 parts at 30° .

Precipitation of the dissolved lime may be brought about by various causes. In the common case of springs escaping from a limestone formation, which are often highly charged with lime, mere exposure to the atmosphere permits so much carbon dioxide to escape that there may be a constant precipitation of the carbonate which in course of time builds up massive deposits of calc-sinter (calcareous tufa). Plants which grow in water and absorb carbon dioxide have the same effect;

indeed the abundance of plant impressions in calc-sinter has led many people to assume that plants play the main part in the formation of these deposits. In this matter, however, it is possible to confuse cause and effect. The calcareous deposit may be associated with plant remains because plants were the cause of precipitation, or alternatively plant remains may be associated with the deposit because an abundance of carbon dioxide escaping from waters favours the growth of plants. E. T. Allen has studied the calc-sinter deposits in the Yellowstone Park and concludes that "the part played by organisms in their formation is geologically unimportant."

Still another cause of precipitation of lime is the production of ammonia by decaying organisms. It has been shown that the bottom mud of the Black Sea is largely composed of powdery calcium carbonate which has been precipitated by ammonia generated from decaying animal matter; and R. A. Daly has contended that many of the unfossiliferous limestones of the Pre-Cambrian may have been formed by a similar process. Still one more possible cause of precipitation of lime may be mentioned; that is the local heating of sea-water by submarine volcanic eruptions. A recent writer has found in this possibility a satisfactory explanation of the frequent occurrence of non-fossiliferous limestones between submarine lava-flows.

So long as one deals with limestones which have not undergone extensive recrystallization, it is possible to distinguish those formed mainly of organic debris from others that are mainly deposits from solution, although it is true that there may be some admixture of the two kinds of material. The calcareous mud which forms the matrix of shell-limestones may be in part a precipitate like that forming in the Black Sea; but generally speaking there is no reason to think that most of the thick fossiliferous limestones owe more than perhaps a trifling part of their mass to precipitation. Even in a fine-grained deposit like the English Chalk the bulk of the material

can be identified as minute shells and fragments of larger shells which have undergone disintegration. Highly recrystallized limestones naturally can not be referred with certainty to either of our two groups; they have lost their original characters and acquired the character of a metamorphic rock.

The deposits of calc-sinter formed by rivers and hot springs are often thick and extensive. In Bahia, Brazil, rivers draining a limestone region have given rise to calc-sinter deposits which locally exceed a hundred feet in thickness. Similar deposits are widely developed in the western states of Italy. Important deposits of calc-sinter about hot springs are known in the Yellowstone Park, where an area of twenty square miles is covered with a deposit reaching 250 feet in thickness. Calc-sinter formed by the drying up of a great lake is largely developed in the Lahontan basin of Nevada. The average thickness of the deposit in this region is about twenty feet, but there are crags and towers fifty to sixty feet high.

Deposits of calc-sinter show no distinct bedding, but an irregular lamination is common. The rock is generally white, with a chalky appearance, and when recently deposited it is porous or dendritic and full of irregular cavities. Plant impressions are common, and snail shells may be embedded in the rock. With increasing age recrystallization sets in, and the cavities become lined with agate-like layers of fibrous carbonate or crystals of calcite. In course of time the mass may become quite compact. "Onyx marble" is a handsome, banded variety of calc-sinter.

Oolite and pisolite are limestones built up of little spheroidal bodies resembling the roe of fishes or heaps of peas. Under the microscope the spherules are seen to consist of needles of calcite, having either a radial or a tangential arrangement. At the centre of a spherule there is often a tiny grain of sand or a fragment of shell which has served as a centre for the deposition of suc-

cessive shells of carbonate. It is sometimes assumed that these spherules are formed around grains of sand which are rolling about on the sea floor, and it is known that they form in hot springs, about grains which are buoyed up by the water. On the other hand, precisely similar structures are developed in glasses and jellies which have begun to crystallize. It has lately been established by experiment that spherulitic structures are formed when an emulsion (containing a substance in the colloidal state) crystallizes. If the substance is pure the spherules have a radial structure; if impure, the structure is concentric. What part, if any, is played by algæ and bacteria in the formation of oolite and pisolite is still undecided.

A limestone may consist entirely of oolitic grains or partly of such grains and partly of shell fragments. A completely oolitic limestone must be considered to be a deposit from solution, but if marine shells are present in addition, as in the Jurassic oolites of England, then the rock should be classed rather with the shell limestones than with the calc-sinters.

Dolomite as well as calcite may be deposited directly from solution. The Rauchwacke of the Permian of Germany is a porous dolomite which is believed to have been deposited as a mixture of dolomite and anhydrite, the latter being afterwards leached out.

In countries that have a long dry season and low rainfall, ground water is drawn up to the surface and evaporates there, depositing lime in the soil. In the course of time there may be formed in this way a nearly continuous sheet of surface limestone with a thickness of several feet. The stuff is nodular and porous, and it encloses a large quantity of sand and boulders belonging to the subsoil. This deposit is just a variety of calc-sinter, but on account of its impurity and its resemblance, when included boulders are numerous, to artificial concrete, the handy name "calcrete" has been applied to it.

(b) IRONSTONE.

Iron is held in solution by surface waters in the form of ferrous bicarbonate, ferrous sulphate, or perhaps as salts of certain organic acids, and it is also carried in suspension as colloidal ferric hydroxide. Deposition of iron occurs principally in shallow, stagnant waters, such as lagoons, lakes and swamps. The causes of deposition are many. Loss of carbonic acid, either by evaporation or by the action of water-weeds and bacteria, will cause ferrous carbonate (siderite) to be precipitated. Exposure to oxidation will precipitate one of the hydrous ferric oxides (turgite, $2\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$; limonite, $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$; xanthosiderite, $\text{Fe}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$) or a ferric humate. Alkaline silicates in the water will precipitate iron silicates and hydrogen sulphide will precipitate iron pyrites or marcasite. Iron is also precipitated by colloidal organic matter; this is the basis of the process of water-purification by means of iron-alum. In view of all these possibilities, it is clear that ironstones may vary a good deal more in composition than limestones do.

Ironstones as well as limestones are often oolitic. This is sometimes held to indicate that oolitic ironstone is a replacement of oolitic limestone, but that is not necessarily the case, for typical grains of iron-oolite have been found in the bottom sands of the North Sea. The spherules often show a nucleus of quartz or calcite, surrounded by concentric shells of hematite and silica, hematite and calcite, or hematite and chamosite. The hematite may subsequently alter into limonite or magnetite. Siderite is also found in oolitic form, and even iron pyrites may be oolitic. The iron oolites of Lorraine and Luxemburg are thought to have been formed from a colloidal suspension of iron and calcium carbonates, with alumina, silica, clay and sand grains. When this suspension was exposed to oxidation, ferric hydroxide was precipitated on the solid particles, thus building oolitic grains.

E. C. Harder has shown that bacteria play a large part in the precipitation of iron. He finds that iron-precipitating bacteria are present wherever iron-bearing waters occur, both underground and on the surface, and that the yellow or brown scum which forms on the surface of such waters consists largely of iron-precipitating organisms, chiefly thread-bacteria. He also showed experimentally that solutions of certain iron salts, when inoculated with "almost any type of natural water or of soil" gave precipitates of ferric hydroxide, thus indicating the almost universal presence in nature of organisms capable of precipitating iron from solution.

The Clinton hematite beds of New York, which are largely oolitic, are interbedded with shale and sandstone and are locally as much as forty feet thick. The "minette" beds of Lorraine and Luxemburg are limonite, in beds up to twenty feet thick. The "black-band ironstones" of Europe and America are impure siderites, and are associated with shales and coal seams. The Cleveland ironstone of the north of England is an oolitic siderite, perhaps replacing limestone.

The conditions under which iron silicates are precipitated are not properly known. Glauconite or greensand is known to be formed in shallow sea water, at depths of more than a hundred fathoms. It is a granular mineral, often disseminated in sandstones and locally forming independent beds or lenses. Greenalite and chamosite are hydrous iron silicates of indefinite composition; both are green and both tend to form oolitic structures. Oolitic chamosite and greenalite beds, often oxidized to hematite, limonite or magnetite, form important iron ores in Minnesota, Bohemia and Transvaal. The principal band of oolitic ironstone near Pretoria, Transvaal, is over 25 feet thick; it shows current bedding and ripple marks. It consists of minute oolitic bodies, built up of concentric shells of magnetite, hematite and chamosite around quartz grains; these are mixed with grains of sand and lie in a matrix of clayey iron oxide.

Beds of precipitated iron sulphide are known in Newfoundland and Westphalia. They are thin and impersistent and have more economic than geological importance.

Deposits of a very impure clayey or sandy limonite are sometimes formed on or just beneath the surface of the soil, either in continuous sheets or as layers of nodules and pellets. The material is usually porous and slaggy in appearance, full of irregular cavities and tubules which may be lined with crusts of fibrous limonite. The colour is blotchy, from brown to red and yellow, or black if much manganese is present. The deposits are due to the oxidation of traces of iron salts brought up by ground water; perhaps soil bacteria play a part in precipitating the iron hydroxide from solution. Such deposits, which contain much admixed sand, have been called "ferricrete."

(c) SILICEOUS SINTER, CHERT, JASPER.

Siliceous sinter (geyserite) is especially associated with hot alkaline springs. The dissolved or suspended (colloidal) silica is precipitated in consequence of cooling, evaporation, or the action of algæ (doubtful). The deposit has the composition of opal, and it forms a light cellular or moss-like mass which, like calc-sinter and phosphorite, may become dense and compact in consequence of recrystallization.

Sands and gravels in dry climates are sometimes cemented together by secondary silica, either chalcedony or opal, forming surface quartzite or "silcrete." The rock has the lustre, hardness and fracture of quartz and may be tightly compacted or full of cavities. Silcrete takes the form of lenses and irregular jagged masses. In some cases it seems to have been formed by replacement of limestone.

Chert and jasper are bedded rocks composed of fibrous or minutely crystalline silica. Chert is very pure and is white or greyish in colour; flint is merely a dark grey to nearly black chert, occurring especially as nodules in chalk. Jasper is an impure form of silica which owes

its bright colours (brown, red, yellow, green) to the presence of large quantities of iron oxides or iron silicates. Chert forms beds, lenses and concretionary masses in many limestones, which it appears to have entered by replacement along the bedding-planes and joints. Some chert beds possibly represent precipitates of silica on the sea-floor; the reason for suspecting this is that analyses of river water show an appreciable content of silica, while sea water shows hardly any. The difference must be due at least in part to precipitation of silica on the sea-floor. Sponge spicules and tests of radiolaria are common in bedded cherts; remains of polyzoa are also to be found, and fragments of brachiopods, crinoids, etc. It is sometimes supposed that chert is a recrystallized radiolarian earth, but the association of radiolaria with chert may be accidental, like that of plant remains with calc-sinter.

Under the microscope chert shows silica in several forms, from isotropic opal to fibrous chalcedony and minutely granular quartz. The spherulitic and interlocking (mosaic) texture of the material shows that it is not detrital but has been formed by the crystallization of a gelatinous precipitate.

(d) ANHYDRITE AND GYPSUM.

Sea-water holds the metallic ions sodium, magnesium, calcium and potassium, in that order of abundance; and the acid radicles Cl , SO_4 , CO_3 and Br . On evaporation of the water the salts are deposited in a definite order, beginning with calcium carbonate, followed by calcium sulphate and sodium chloride. The remaining salts hardly concern us, their significance as rock-formers being negligible.

Calcium sulphate may be deposited either as anhydrite, CaSO_4 , or as gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. It has been shown experimentally that anhydrite normally separates from solutions of calcium sulphate above 66°C . (150°F .), but that in presence of sodium and magnesium chlorides anhydrite is formed even at 25°C . (77°F .). In the

Stassfurt salt deposits the first salt to be formed was gypsum, but afterwards, when the concentration of sodium chloride was increased by evaporation, anhydrite and rock salt were deposited in alternate layers, a few millimetres of anhydrite being followed by a few centimetres of salt. So regular are these layers that they are thought to be annual deposits. In the synclines of the Fars series in western Persia the lower beds are largely salt with anhydrite, the upper beds chiefly gypsum and clay. But beds that now consist of gypsum may have been laid down as anhydrite and afterwards hydrated by ground or surface water. This change has undoubtedly taken place to some extent in Persia, and it has been demonstrated in several other regions. At Bex, in the canton of Waedt, Switzerland, gypsum is said to pass into anhydrite within sixty to a hundred feet from the surface. The reverse process, dehydration of gypsum, is also possible but there is nothing to suggest that it takes place in nature.

On account of its susceptibility to hydration, anhydrite is seldom exposed at the surface, but beds of anhydrite intersected in boreholes are often scores of feet thick. In an exceptional instance in Texas the drill passed through more than 1,100 feet of anhydrite in the form of a continuous, laminated deposit. The gypsum of Hillsborough, Nova Scotia, which has been formed from anhydrite, is 250 feet thick. In western Persia, beds of gypsum and anhydrite occur in a belt of country measuring 1,000 miles by 50 miles, and single beds of gypsum are often fifty feet thick. J. V. Harrison has calculated that to form the gypsum deposits of this region "a sea such as the Indian Ocean . . . would have had to supply water to a depth of one mile from its surface." The difficulty of accounting for evaporation of the oceans on such a scale has led some geologists to look for other sources of supply. The action of volcanic gases on limestone has been suggested; also the oxidation of iron pyrites, or of hydrogen sulphide derived from decomposing organic matter, followed by a reaction between the

sulphuric acid so formed and limestone. Harrison has actually observed the conversion of limestone into gypsum about sulphur-springs in Persia.

While it is undeniable that some gypsum is formed by such reactions, we must still seek a marine source for most of it, especially when it is interbedded with clay, salt and shelly sandstones. After all, it is not necessary to suppose that the huge quantity of calcium sulphate contained in the Fars series of Persia (or in any other large gypseous area) was ever dissolved in the sea *all at one time*. The Eurasian region where the greatest deposits of gypsum and anhydrite are found was beneath the sea during the Paleozoic era and has been an unstable region since the Mesozoic, waves of elevation and of submergence sweeping across it in succession. At any moment since the Mesozoic there has been some calcium sulphate above sea-level and another portion in the floors of the basins, with a third fraction, probably much smaller than either, in process of transportation from one site to the other. Only this small third portion was actually in solution at any moment. One must think of these great gypsum deposits as being "made over" again and again in the same region since Mesozoic or perhaps since Permian times. Only in this way can one account for such vast deposits of calcium sulphate in restricted areas without the necessity for evaporating entire oceans or imagining volcanoes which belched out unheard-of quantities of sulphuric acid. Some gypsum is even transported in the form of sand and mud.

The outcrops of thick beds of gypsum are scored with rain-furrows separated by knife-like ridges, and swallow-holes and other solution channels abound. The beds may be massive or laminated, and the laminæ often show a remarkable degree of folding or puckering, which is generally interpreted as a consequence of the expansion accompanying the hydration of anhydrite. This transformation involves an increase in the volume of the rock which may approach sixty per cent. (one volume of anhydrite is equivalent to 1.62 volumes of gypsum). But

folding and puckering may also be a consequence of the yielding of the soft gypsum beds to compression.

Under the microscope anhydrite appears in grains and parallel or radiating groups of prisms with well-marked rectangular cleavage. Refraction and birefringence are both high. Gypsum forms interlocking plates, laths and needles which have quite a resemblance to mica in consequence of their perfect cleavage, but the refractive index is lower than that of Canada Balsam and the birefringence is also low. Gypsum which has been formed by transformation of anhydrite may enclose remnants of the latter mineral, and tiny rhombs of dolomite are also common enclosures in gypsum.

Alabaster is the name given to a pure, granular gypsum-rock.

(e) ROCK SALT AND OTHER SALTS.

For obvious reasons rock salt is little in evidence among surface rocks except in very dry regions. Nevertheless, the structural features of rocks that do outcrop at the surface may be due to the presence of salt beds in depth. By the removal of salt in solution the overlying beds may be caused to collapse, and folding and brecciation may result. Salt beds also yield very easily to deforming forces, and in regions of compression actual sliding may take place, a salt bed acting as the sole of a thrust-plane. Exploration with the drill has shown that beds of salt often swell rapidly into dome-like bodies which are intruded into younger strata in the same fashion as stocks and pipes of igneous rock. These salt-domes are roughly circular in cross-section, and in the Mexican Gulf region they are found to be situated at the intersections of faults. The salt-plugs of southern Persia were formed from Cretaceous and Miocene salt beds which were forced into plastic flow in consequence of late Tertiary mountain-building movements and overthrusts. When the salt reached the earth-surface it often continued to flow like a glacier, under its own weight.

The thickness of a salt-dome may be several thou-

sand feet. Single beds of salt are not infrequently measured in tens and sometimes in hundreds of feet in thickness. The associated rocks are mostly anhydrite, gypsum, and clay or shale. The chief body of salt at Stassfurt is nearly a thousand metres thick and consists of alternate layers of salt and anhydrite, each salt layer being about eight centimetres thick and the anhydrite layers a tenth of that.

Sodium nitrate forms an extensive sub-surface deposit ("caliche") in the arid regions between the Andes and the Pacific. It is associated with sodium chloride and other salts, and mixed with sand and stones. The deposit seems to have been formed by the evaporation of ascending ground water, in the same way as surface limestone or calcrete. It is a "salcrete."

Sulphates, carbonates and borates of the alkalies are sometimes found in beds of appreciable extent among the deposits of salt lakes.

SUGGESTIONS FOR READING.

- T. C. BROWN, *On Oolites and Oolitic Texture in Rocks*. Bull. Geol. Soc. America, 1914, p. 745.
- J. JOHNSTON and E. D. WILLIAMSON, *The Role of Inorganic Agencies in the Deposition of Calcium Carbonate*. Jour. Geol., 1916, p. 729.
- H. C. SARGENT, *The Massive Chert Formation of North Flintshire*. Geol. Mag., 1923, p. 168.
- W. A. TARR, *Origin of the Chert Beds in the Burlington Limestone*. Amer. Jour. Sci., vol. XLIV., 1917, p. 409.
- E. C. HARDER, *Iron-depositing Bacteria and their Geological Relations*. U.S. Geol. Survey, Prof. Paper 113, 1919.
- J. V. HARRISON, *The Gypsum Deposits of S.W. Persia*. Economic Geology, 1924, p. 259.
- B. SMITH, *The Chellaston Gypsum Breccia*. Quart. Jour. Geol. Soc., 1918, p. 191.
- W. H. BUCHER, *On Oolites and Spherulites*. Jour. Geol. 26, 1918, p. 593.
- J. V. HARRISON, *The Geology of some Salt-Plugs in Laristan*. Quart. Jour. Geol. Soc. London, 1930, p. 463.
- E. T. ALLEN, *The Agency of Algae in the Deposition of Travertine, etc.* Amer. Jour. Sci., vol. 28, 1934, p. 373.
- W. H. TWENHOFEL, *Principles of Sedimentation*, 1939.

CHAPTER XII.

SEDIMENTARY ROCKS.

CLASS III—CRYSTALLINE ROCK-RESIDUES.

These rocks are formed mainly of the larger fragments set free by mechanical weathering, that is, of boulders, pebbles and sand grains or what has been called "rock flour," and they hold little of the fine "rock rot" which is a characteristic product of chemical weathering. That is to say, the great majority of the grains are fragments of crystals or of crystalline aggregates, and colloidal matter plays only a minor part. Among such rocks one may draw a useful distinction between those formed of angular fragments which have suffered little corrosion and those composed of well rounded fragments. Rocks of the former type are typically terrestrial deposits; those of the latter character are to an overwhelming extent sub-aqueous. But when the size of grain becomes very small the distinction disappears, for grains which are small enough to be carried in suspension by water or wind never become round.

(a) BRECCIA AND TILLITE.

Breccia is a deposit containing a large proportion of coarse, angular rock-fragments. Such a deposit may be formed by weathering in place, the lighter products of weathering being washed away by rain or blown away by wind and the stony residue cemented by lime, silica or limonite. The more stony examples of calcrete, silcrete and ferricrete are breccias of this sort. A breccia may also begin as a heap of talus at the foot of a cliff or in a

valley between mountains, and landslips and avalanches may make their contribution to the mass. A coarse glacial deposit is also a breccia, but the distinctive name of tillite is given to it. A volcanic breccia differs from other coarse-grained rocks as regards both the forces that produced it and the nature of the material composing it; it is generally termed agglomerate and will be discussed later.

There remains a group of breccias formed by crustal movements. One well-established type has been formed by the collapse of an overlying formation when the underlying one, usually a bed of limestone, salt or gypsum, has been leached out from beneath it; and another type is developed along fault-planes and zones of crushing. The former kind should be retained among the sedimentary rocks, for it keeps to a definite horizon in the sedimentary succession, but a fault-breccia can by no stretch of imagination be regarded as a sedimentary rock. The fault-breccias and the related mylonites and flinty crush-rocks are neither sedimentary nor igneous but find their proper home among the metamorphic rocks.

The boulders in a breccia may be of any kind of rock that is neither too soft nor too soluble; even sun-dried flakes of clay may give rise to a breccia, but usually the boulders are of sandstone, limestone, or some eruptive rock. They may be very large; blocks of limestone in breccias about the rock of Gibraltar are sometimes twenty to thirty tons in weight; and a characteristic feature of this kind of deposit is that there has been very little grading of the fragments and there is hardly a trace of stratification. In some cases, however, talus has been worked over by intermittent streams, and then the boulders may show signs of corrasion and there may be some degree of grading and stratification, indicating a passage from breccia towards ordinary conglomerate.

The cementing material of breccias is usually lime, silica, or oxides of iron or manganese; but in special circumstances it may be barite, fluorite, gypsum, siderite,

or another of the "sparry" veinstones. At Bex, Switzerland, a breccia of limestone and anhydrite that was met in the salt mines was cemented by rock salt.

Coarse deposits of glacial origin get the name of till or boulder-clay when they are unconsolidated, and of tillite when they are cemented together. Characteristic features of till and tillite are the lack of sorting or grading of the material (unless it has been worked over by glacial streams), so that huge boulders may lie among the silt; and also the angular form of the boulders, which may show one or more flattened and striated facets. The smaller fragments are sharply angular, and all are perfectly fresh, having been preserved from weathering by being encased in ice. It is clear that rocks of almost any kind may be found in boulder-clay, but it is more especially the harder and tougher rocks that survive prolonged grinding beneath the ice. Boulders of granite, quartzite and crystalline limestone are common.

Without the evidence of striations on the boulders and on the floor upon which the deposit rests, it may be impossible to distinguish a tillite from a talus-breccia. If the deposit has been rearranged by running water then it may be well graded and stratified, and it will gradually cease to be distinguishable from ordinary gravel and sand.

(b) AGGLOMERATE AND TUFF.

Agglomerate is a volcanic breccia composed of large and small fragments of any kind of rock, that have been thrown up into the air by volcanic explosions and have accumulated round about the vent. The material may be largely composed of "cinders" or lumps of slaggy lava, together with lapilli and volcanic sand; but it is not necessary that any volcanic material should be present at all; for the agglomerate may be made up entirely of fragments of the rocks through which the volcano broke its way to the surface. Layers of agglomerate may alternate with beds of volcanic sand or thin sheets

of lava, but apart from this there is little sign of stratification and the layers are most irregular in thickness. The name "volcanic bomb" is given by some writers to pear-shaped or comet-shaped lumps of lava with a rounded head and a distinct tail which may have a spiral twist in it. It is said that these bombs acquire their curious shape during their flight through the air, but the writer has spent many hours on the top of Mt. Vesuvius, watching the flying lumps of lava through a powerful field-glass, and he is satisfied that the shape originates at the moment when the bomb is torn apart from the upflung tongue of lava in the vent, and that it is not modified during the flight of the bomb through the air.

Many of the larger blocks thrown out during explosions fall back into the throat of the volcano, which may even become choked by its own debris. A good deal of the kimberlite of the South African diamond pipes, for instance, is really a volcanic breccia consisting of fragments of shale, granite, quartzite, eclogite and other rocks, all cemented together by a matrix of serpentine. Similar volcanic breccias have been described near Montreal, in which as much as nine-tenths of the material consists of boulders of quartzite, sandstone, limestone and granite enclosed in a matrix of melilite-basalt. In one case the breccia holds pieces of a geological formation that has been entirely denuded away from the area; these pieces must have fallen more than two thousand feet down the vent.

Flow-breccia is a kind of volcanic breccia formed by the freezing of the top of a moving stream of lava. The solid crust gets broken up by the movement of the liquid underneath it, and the lumps of slaggy lava are tumbled and jumbled into heaps of flow-breccia until the mass can move no further.

Tuff is the name given to rocks composed of the smaller fragments and volcanic "ash" (sand or dust) deposited at a greater distance from the vent than agglomerate. The finest dust is often blown to great

distances, and may be carried out to sea. In settling under water it is likely to be mixed up with ordinary marine sediment, forming sandy tuff and tufaceous sandstone. The grains in tuff often include quite a lot of well-shaped crystals of minerals such as augite, leucite, melanite, anorthite, which must have been present in the lava before the sudden liberation of gas that blew it to bits. The greater part of most tuffs consists simply of comminuted rock fragments. If these fragments are mostly of rocks other than lava then the volcanic origin of the deposit may be obscured; for instance, it may be taken for a graywacke; but the presence of scraps of glassy pumice, full of gas bubbles, is a distinctive character of a fresh tuff. Charred remains of vegetation are sometimes to be seen in tuff. It is obvious that the mineralogical composition of a tuff can vary just as widely as that of lava. It is usual to name tuffs according to the nature of the recognizable rock fragments, as rhyolite tuff, basalt tuff, and so on.

(c) CONGLOMERATE.

Conglomerate is a consolidated gravel deposit which once formed a sea-beach or the bed of a torrential river. The coarser beds may hold boulders a foot or two in diameter, but sizes from six inches downwards are commoner. The degree of rounding of the pebbles is inversely proportional to the size. Really spherical pebbles are rare, but ellipsoidal and bun-shaped pebbles are common enough. The shape of a pebble must depend on the character of the rock from which it was formed; thus a sandstone or schist will give a discoidal pebble with two more or less flat faces parallel to the bedding-planes; but a granite, a porphyry or a serpentine, being almost without structural planes, may give nearly spherical pebbles. Since the rounding of the pebbles is a consequence of the prolonged milling which they have undergone in the zone of wave-action, it is to be expected that only the hardest or toughest of rocks

will survive. The commonest pebbles in conglomerate are of such rocks as quartzite, chert, jasper, vein-quartz, rhyolite and granite. Limestone pebbles are not often found in association with harder pebbles such as those just mentioned, but in some localities there are conglomerates composed almost entirely of boulders and pebbles of crystalline limestone. Basic igneous rocks such as dolerite and basalt are very seldom found as pebbles in conglomerate. Mr. Lamplugh has pointed out that in the gorge of the Zambezi river below the Victoria Falls great boulders of basalt are common, but there are no basalt pebbles and no basalt sand. "It seems as if the basalt blocks, when once broken into fragments, are soon completely disintegrated."

In the banket or gold-bearing conglomerate of the Witwatersrand the pebbles are entirely siliceous, mostly vein-quartz but some of quartzite and chert. These pebbles have clearly suffered an extreme amount of milling by waves and currents, since all but the hardest kinds have disappeared completely, yet even in the banket it is rare to find a really round pebble, most of them being slightly ellipsoidal.

The pebbles in a conglomerate are generally well graded, the larger beneath the smaller; this is the only kind of stratification that is possible in such a coarse deposit. But partings of sandstone often lie between the pebble layers, and then the bedding is unmistakeable. If the separation of sand and gravel has been complete, as it often is on storm-beaten coasts, then the deposit will consist of pebbles in contact with one another, the interstices remaining almost empty. Conglomerates having this character do not seem to be known, from which it would seem that as soon as a gravel bed sinks below the zone of wave action the interstices are filled by sand which seeps down from above. The spaces between the pebbles being filled in this way, the whole mass is eventually cemented together by silica or sometimes by lime or iron oxide. A conglomerate with

siliceous cement is often so strong that it will break through rather than round the pebbles.

Fossils are very seldom to be found in conglomerate, but teeth and the enamelled scales of fishes are sometimes able to survive the pounding of the pebbles.

A volcanic conglomerate is something entirely different from the conglomerates described above. It is true that the name volcanic conglomerate is sometimes given to an ordinary conglomerate in which the pebbles are formed of a volcanic rock, but the term is not needed in that sense. By a volcanic conglomerate we mean a curious variety of agglomerate in which the boulders, instead of being angular, have been more or less perfectly rounded by being tossed up and down in the throat of the volcano—a sort of cup-and-ball action. The matrix is composed entirely of dust of the same composition as the balls. A volcanic conglomerate may look like an ordinary conglomerate, but instead of being stratified it typically occupies a volcanic neck. The rock is generally a very basic one—basalt, melilite basalt, lamprophyre or peridotite.

(d) GRIT, ARKOSE AND GRAYWACKE.

Grit is a coarse sand mostly formed of angular quartz grains, and arkose is a kind of grit containing a great deal of fresh feldspar. Grit may form under any climatic conditions, but true arkose is a deposit of the arid regions where granite has been broken up by extreme changes of temperature and the fragments have suffered little or no chemical alteration. Such deposits may be assorted by wind and occasional torrential rains, but stratification is generally poor, although there may be current-bedding. Besides quartz and feldspar, garnets, magnetite and other hard minerals may be present in grit or arkose. The cementing material is commonly silica.

Graywacke is an old-fashioned name that is applied to certain peculiar sediments of the older Paleozoic systems of Europe. Graywacke may have as great a range of

composition and texture as sandstone does, but according to the German usage it is essentially a dark-coloured grit, containing fragments of schist, slate, quartzite, and sometimes scraps of dark minerals such as hornblende and chlorite. The matrix is a fine dust of similar composition, which may be darkened by carbonaceous matter. Graywacke was probably formed under similar physical conditions to arkose, but from different materials.

(e) SANDSTONE AND QUARTZITE.

The term sandstone is applied to any rock the grains of which are not more than one or two millimetres in diameter. It is not necessary that the grains should be of quartz, though they are usually so; sands formed entirely of shell-fragments or grains of phosphorite, garnet, or magnetite are known. Quartz is the most abundant constituent of the great majority of sandstones, and some of them contain almost nothing else; but many other minerals play an important part in these rocks. Feldspar grains, which may be either orthoclase or plagioclase, are fairly common though they do not play such a large part and are not so well preserved in subaqueous sandstones as in a terrestrial arkose. The latter rock is so characteristic of weathering under arid conditions that it would be well if the name arkose could be restricted to the terrestrial deposits, the sub-aqueous ones being called feldspathic sandstone or something else. One of the most constant constituents of the quartzose sandstones is muscovite, in tiny silvery scales which show up strongly on the bedding-planes. Garnets, magnetite and ilmenite are also common; tourmaline and epidote are more restricted in distribution, and augite and hornblende are sporadic. Quite a host of other minerals can be detected by crushing sandstone and concentrating the heavy residues. Among these are rutile, anatase, zircon, apatite, staurolite, kyanite, barite, tinstone, fluorite, monazite, pyrite, topaz. Glauconite is an important constituent of the marine greensands.

In addition to these crystalline fragments there is generally a small proportion of the clay-silicates, and when this becomes important the rock passes through argillaceous sandstone into shale. Carbonaceous matter derived from plant-remains is present in some sandstones; and shell-fragments may be mingled with the mineral grains.

The grains of sand are generally well rounded, but with diminishing size the degree of rounding falls off. It is only grains that are large enough to be *rolled along* by currents of water or wind that become rounded; particles small enough to be lifted up and floated along, either as dust in the air or as silt in water, do not become round. The most perfectly rounded grains are seen in desert sands, the most angular in river sands. Marine sands come between these, with the majority of the quartz grains at least sub-angular to moderately rounded.

The cementing material in marine sandstones is mostly calcite derived from shells, but it may be glauconite. In freshwater sandstones, which are in general more argillaceous than marine ones, the cement is commonly clay or limonite. Desert sands and all very siliceous sands and grits have silica as the characteristic cementing material. This is often deposited upon rounded quartz grains in such a way as to restore the crystalline form, and the sand then appears as an aggregate of tiny quartz crystals. More complete cementing leads to the formation of a quartzite, in which the grains fit together tightly, with fretted, interlocking margins and practically no interstices. Such a quartzite breaks like a quartz crystal, with conchoidal fracture and glassy lustre. Gypsum is found as a cementing material about salt-pans and in lagoon deposits. Bitumen is the cementing material of sandstones in certain petroliferous formations. Other minerals such as barite and phosphorite form the cement in special cases.

Sandstones are generally excellently stratified, and unless they have been quartzitized they split easily along

the bedding-planes. The test of splitting under the hammer is the easiest way of distinguishing a sandstone from a quartzite. False-bedding is developed especially in æolian sands and delta deposits. Fossils in sandstone are usually represented by moulds and casts, the original shell-substance having been dissolved completely away.

(f) SILTSTONE AND LOESS.

The name siltstone has come into use in recent years to denote rocks which are rather too fine-grained to be called sandstone and do not quite have the constitution of clay. The grains, which run from about .05 to .005 mm. in diameter, are largely composed of quartz, feldspar and muscovite, with tourmaline, zircon, and other accessory minerals of rock flour, but there is a small proportion of clay silicates too. Siltstone is the subaqueous equivalent of dust and loess.

Loess (löss) is sometimes described among the clays, but both mineralogically and texturally it is a silt rather than a clay. It holds little of the true clay-silicates, and it is essentially a deposit of dust or fine rock-flour transported by wind. Some deposits which will satisfy this definition may be found in almost any country, but it is especially in the semi-arid regions to leeward of the great deserts that thick deposits of loess are found. The loess of China is locally more than a thousand feet thick, and it extends far up the slopes of mountains where no agent but wind could possibly have deposited it. The particles that compose loess are small, measuring a few hundredths to a few thousandths of a millimetre, and are highly angular. The minerals present are especially quartz, feldspars and mica, with calcite and iron oxides; a small proportion of clay-silicates may be present in addition. There is so little cementing matter (except in certain layers where calcareous concretions are largely developed) that loess can be rubbed down to powder with the fingers. The deposit shows little or no stratification, and no fossils are found except snail-shells and plant im-

pressions. In short, true loess is a terrestrial silt, accumulating in semi-arid regions, but there is no mineralogical difference between this and silt laid down under water.

SUGGESTIONS FOR READING.

- J. E. MARR, *Deposition of the Sedimentary Rocks*, chaps. 7 and 8.
W. H. TWENHOFEL, *Principles of Sedimentation*, chap 8.
J. A. UDDEN, *Mechanical Composition of Clastic Sediments*. Bull. Geol. Soc. Amer., 1914, p. 655.
D. C. BARTON, *The Geological Significance of Arkose Deposits*. Jour. Geol., 1916, p. 417.
C. W. TOMLINSON, *The Origin of Red Beds*. Jour. Geol., 1916, pp. 161, 238.
E. T. MELLOR, *The Glacial (Dwyka) Conglomerate in the Transvaal*. Quart. Jour. Geol. Soc., 1905, p. 679.
P. E. RAYMOND, *The Pigment in Black and Red Sediments*. Amer. Jour. Sci., vol. 240, 1942, p. 658.
G. B. BARBOUR, *The Loess of China*. Ann. Rep. Smithsonian Inst. for 1926 (1927), p. 279.
L. V. PIRSSON, *Microscopic Characters of Volcanic Tuffs*. Amer. Jour. Sci. 40, 1915, p. 195.

CHAPTER XIII.

SEDIMENTARY ROCKS.

CLASS IV—CRYPTOCRYSTALLINE AND COLLOIDAL ROCK-RESIDUES.

This class includes the clays, mudstones, shales and slates; it is convenient to speak of them in general as *claystones*. These rocks are characteristically formed of rock rot, the amorphous, scaly and fibrous products of rock-weathering; but along with this material there is always a considerable proportion of very finely divided rock flour composed mainly of quartz, feldspar and white mica. To identify these crystalline particles is not difficult if one uses a sufficiently high magnification; but the microscope gives little help in the case of crypto-crystalline (scaly, fibrous) and colloidal (amorphous, spongy) matter. Chemical analysis of this sub-microscopic matter shows it to contain silica, alumina, iron oxides, smaller quantities of soda, potash, lime and magnesia, and between three and twelve per cent. of water; but since different clays hold different proportions of these oxides it is clear that clay must be a mixture of various compounds, especially hydrous silicates and hydroxides. Alumina seems to be able to combine with silica and water in many proportions, giving rise to a series of compounds which have the power of incorporating ions of the alkalis and alkaline earths. The principal aluminosilicates that are known to be formed by the decomposition of rocks were summarized in Chapter IX.

Kaolinite is the typical clay-silicate; it was formerly thought to be formed only under hydrothermal condi-

tions, but is now known to be produced on a large scale by atmospheric weathering, especially under acid conditions. Clays of the montmorillonite group are also among the more abundant products of atmospheric weathering. In addition, chlorite, serpentine and calcite are likely to be mixed in variable proportions with the clay-silicates.

In addition to aluminosilicates, the hydroxides of alumina and iron play a part in the constitution of many clays, especially in tropical and subtropical regions. Laterite is a dark brown clay composed largely of these hydroxides, with some free silica and admixed silt. It is formed in great thickness in many hot countries and there is a voluminous literature about it. Bauxite is nearly pure aluminium hydroxide with a composition approaching $\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$. It is regarded by some students as a definite mineral, but others hold it to be a mixture of amorphous diasporite and gibbsite.

The term clay, then, has no very definite mineralogical or chemical connotation. It is a popular term, not a scientific one, and all that it connotes in popular usage is an exceedingly fine-grained rock which has the property of plasticity when wet. The average grain-size is less than .005 millimetre, the particles of true clay-substance being very much smaller than this. The property of plasticity is believed to be connected with fineness of grain, the most plastic clays being excessively fine-grained, but not all clays are plastic. When clay is heated to more than 600°C . its plasticity is permanently lost.

Almost every clay contains some admixed rock flour, consisting of minute particles of feldspar, quartz and other anhydrous minerals. It has been shown in the case of some Swedish clays that this fraction is made up of alkali-feldspar and quartz in the proportion of two to one. Other detrital grains that have been identified in clays are mica, epidote, calcite, rutile, zircon, sphene. Of the remainder, composing the true clay-substance, part is soluble in acid while the remainder is insoluble and seems to be

made up of various aluminosilicates, including micas and chlorites.

The detrital particles in clay are quite angular. There may be a complete lack of orientation, or the flatter particles may lie in parallel position. Some clays are distinctly banded or laminated, the separate layers varying from less than a millimetre up to one or two centimetres in thickness. Each layer is silty in its lower part and carries the finest clay at the top, where it is followed immediately by another silty layer. These bands are called varves, and it has been possible to show, in Sweden and elsewhere, that the varves are annual layers.

The characters of a clay vary considerably according to the conditions of accumulation. Residual clays (those still lying in place upon the rocks from which they were formed) are impure and unstratified, and they are generally brightly coloured in consequence of complete oxidation of iron. Laterite and bauxite belong to this type. Lacustrine clays are bedded and often contain much carbonaceous matter in the form of rootlets. Marine clays are well graded and laminated, perhaps because the particles had to sink through a considerable depth of water. The colour is often bright red, indicating complete oxidation of iron; but if reducing conditions prevailed on the sea floor then the colour is blue or black. A green colour may be due to glauconite.

Glacial clays differ from other clays in having a larger share of fine silt in proportion to true clay-substance. The best examples of varve-clays are glacial in origin. Volcanic clays are formed by the decomposition of volcanic ash. Deposits of this nature have been recognized in several formations in America and have been called bentonite. The clay is white or light grey, well stratified and fissile, and it swells up largely when put in water. It is essentially composed of fragments of devitrified glass.

Loess is sometimes described as an æolian clay, and it may be that some loess deserves such a description, but a great deal of what is called loess in Europe is just

a terrestrial silt or dust, as described in the last chapter, and has no claim to the title of claystone.

Shale and mudstone are consolidated clays, the former being distinctly laminated and the latter not. During the consolidation of clay to shale there is a loss of three to five per cent. of water, involving a closer packing of the particles and a loss of plasticity. Some shales can be made plastic again if they are finely ground and thoroughly mixed with water, but wetting alone does not restore shale to the state of clay. The consolidation seems to be accompanied by some degree of crystallization of the amorphous base of the clay, which cements the particles together. The lamination of shale is a primary character, developed during deposition of the material; but the fissility of shale, or the property of splitting into thin sheets, is certainly increased by compression. Under the microscope, scales of muscovite and chlorite and particles of quartz, calcite and limonite may be recognized, together with needles of rutile, in a dark, structureless background.

Shales may be calcareous, dolomitic, bituminous, carbonaceous or pyritic. By the oxidation of iron sulphides in shale, efflorescences of iron-alum are formed; such shales are called alum-shales. The average content of water in shale is about five per cent.

Long-continued pressure, especially the tremendous pressure that accompanies mountain-building movements, brings about a still further degree of compacting and gives rise to a slate. There is a further loss of water, coupled with a distinct growth of sericite and chlorite scales in the groundmass, so a slate has a more lustrous look than a shale. A still further stage of recrystallization gives a phyllite, in which the scales of mica are large enough to give a glittering appearance to the rock. As a further consequence of compression, slates and phyllites develop a very perfect cleavage at a high angle to the direction of greatest pressure, and the original bedding-planes may be quite obscured.

SUGGESTIONS FOR READING.

- H. RIES, *Clays, their Occurrence, Properties and Uses*. New York, 1927.
- F. DIXEY, *Lateritization in Sierra Leone*. Geol. Mag., 1920, p. 211.
- W. H. TWENHOFEL, *Principles of Sedimentation*, pp. 293-318.

CHAPTER XIV.

METAMORPHIC ROCKS

METAMORPHIC ROCKS IN THE FIELD.

Metamorphic rocks are those which have been so changed by the action of heat or pressure, aided sometimes by magmatic fluids, that they can no longer be referred readily to their proper classes.

By insisting on the agency of heat or pressure we exclude from the group not only the products of weathering but also such rocks as dolomite and phosphorite, formed by transformation of limestone, and gypsum formed by transformation of anhydrite at low temperature. These rocks are metamorphic in the literal sense, but they can be placed without difficulty in their proper classes in the sedimentary division and it is better to leave them there. On the other hand, we do not necessarily exclude crystalline limestone from the metamorphic division, since heating and compression are known to promote the recrystallization of calcareous rocks. Siliceous rocks that are still in an early stage of metamorphism, such as slates and phyllites, many quartzites, also serpentized peridotites, can be referred without difficulty to their proper classes and nothing is gained by removing them from these classes. There remain in the metamorphic division the following kinds of rocks:—

- I. *Mylonites* or rocks which have been metamorphosed by crushing without recrystallization.
- II. *Hornstones* (German *Hornfelsen*) or rocks which have been partly recrystallized by the action of heat.
- III. *Crystalline schists* or rocks which have been completely recrystallized by heat and pressure.

MYLONITES.

The name mylonite or milled rock was given by Lapworth to fine-grained, flinty rocks which have been produced by crushing and shearing. Typical mylonites are banded or streaky, cleavable rocks composed of indurated rock powder in which eyes of uncrushed rock may persist. It is convenient to use mylonite as a general name for all metamorphic rocks which are characterized by crushing without appreciable recrystallization.

Belts of crushing have no necessary relation to the bedding-planes or other original structures of rocks; in general they intersect the beds at high or low angles, and in this respect crush-rocks resemble eruptive rather than sedimentary rocks. Indeed, in regions of intense compression the crushed material may actually be injected into fissures in surrounding rocks. On the other hand, the fragmental character of many mylonites brings them into closer relation with sedimentary than with eruptive rocks. It is not surprising, then, that mylonites have in some cases proved most puzzling to field geologists meeting them for the first time. In India, King and Foote encountered veins of a dense, black rock cutting gneiss in the Salem district of Madras; they took it to be an igneous trap or basalt and they described the whole complex of gneiss and black veins as "trap-shotten gneiss." Thirty years later T. H. Holland showed that the supposed trap was composed of pulverized gneiss which had been fritted together by the heat generated in belts of crushing. The present writer fell into the same error when he first found dykes and veins of apparent basalt cutting gneissose granite in the Orange Free State. It was only by an elaborate comparison of material in different stages of crushing, supported by chemical analysis of the granite and the vein-material, that he was able to show that the black rock was just finely pulverized granite, compacted by heat. The name "pseudotachylyte" was given to this rock in view of its resemblance, in the thinner veins, to tachylyte or basalt glass.

The pseudo-tachylyte of the Orange Free State is associated with a great dome of granite which, together with the overlying sedimentary rocks, was raised up and strongly fractured in consequence of the intrusion of a younger magma beneath it. The veins of pseudo-tachylyte shoot through the granite in all directions. They are most irregular in thickness and inclination; they branch and intersect each other freely; and the wider veins are crowded with rounded lumps and angular fragments of granite. The veins are not confined to the granite but are found in all the associated rocks, including quartzite, dolerite and amphibolite. Chemical analysis has shown that the pseudo-tachylyte has in every case the same chemical composition as the rock that it cuts, thus it is clear that basalt plays no part in its composition.

Jehu and Craig have described a remarkable belt of crushing which extends for seventy-five miles through the islands of the Outer Hebrides. In South Uist and North Uist the crush-zone has a well defined base, which is interpreted as a thrust-plane along which a great sheet of gneiss has been overthrust from east to west. The sole of the thrust sheet is composed of pseudo-tachylyte, dipping towards the east at an angle of 16° to 27° . The thickness of this sole is in places as much as a hundred feet, and it passes gradually upwards into crushed and sheared gneiss which is injected and veined with pseudo-tachylyte. On South Uist the width of the belt of crushed rocks exceeds two miles, and a second overthrust sheet, which also has a sole of pseudo-tachylyte, is superimposed upon the first.

In the San Andreas fault zone of California, Waters and Campbell record a large development of mylonite, with "every stage in the demolishing of original coarse-grained rocks to an ultramicroscopic paste."

Pseudo-tachylyte seems to be formed only in very hard rocks which offer great resistance to crushing; under these circumstances so much heat is developed that the

rock-powder is all but melted. Softer rocks yield more easily and little heat is developed; but besides this, the character of the product must be affected by the presence or absence of ground-water. It is likely that pseudotachylite is formed when the rocks are dry; and that in presence of interstitial water the temperature does not rise so high and the pulverized material tends to be recrystallized without melting. G. W. Lamplugh has described belts of crush-breccia in a series of slates and grits in the Isle of Man. The breccia, which is several hundred feet wide and extends for a dozen miles, consists of angular to rounded and lens-shaped or spindle-shaped fragments of grit in a slaty matrix. There is no suggestion of fusion, but there has been a little recrystallization in the matrix of the breccia, and scales of sericite and chlorite have formed around the lumps of grit and along shear-planes.

Recrystallization of the groundmass of a crush-rock, of which the beginnings are seen in the above instance, must ultimately produce a type of rock in which new crystallization obliterates the evidence of crushing. Cases are on record of the passage of a brecciated igneous rock into a completely crystalline schist. In the early stages one sees blocks of rock separated by mere films of scaly matter; then boulders scattered through a schistose matrix; and finally a completely schistose rock in which no uncrushed lumps remain. The breccia has become a mica- or chlorite-schist.

HORNSTONES.

Hornstones are typically developed in the contact zones about great igneous intrusions. Argillaceous and calcareous rocks are particularly susceptible to thermal metamorphism and show a characteristic series of changes in the neighbourhood of an intrusive mass. The first change seen in a slaty rock is the appearance of little spots which stand out in relief on weathered or eroded surfaces. The spots are centres of new crystallization,

but it is very difficult to make out what it is that is crystallizing—perhaps andalusite or cordierite. Then a general recrystallization of the clay-silicates begins, leading in the first place to the appearance of minute scales of sericite which give a silky glitter to the cleavage planes of the slate. Later on distinct crystals of andalusite or cordierite develop, and the base of the rock becomes a granular aggregate of quartz, feldspar and mica, often holding needles of sillimanite or tiny garnets. Meanwhile the fissility of the slate has been obliterated and it has become compact, with an irregular, splintery, fracture; it is now a hornstone. Most hornstones are fine-grained rocks but when recrystallization has taken place under favourable conditions one may find a hornstone composed of interlocking grains half a centimetre in diameter.

Sandstones give quartzites by thermal metamorphism, and pure limestone gives crystalline marble. These rocks may be regarded as varieties of the genus hornstone. Impure limestones, or limestones to which silica has been added by magmatic solutions, develop various calcium silicates such as wollastonite, diopside, garnet or vesuvianite, and are then called lime-silicate hornstones. It is time that this awkward name was replaced by something more compact, and the word *marmorite* is suggested. Basic igneous rocks such as basalt and dolerite may also be recrystallized by the heat of an igneous contact and pass, with loss of the original texture, into granular diabase-hornstone.

The outstanding feature that distinguishes a hornstone from a crystalline schist is the absence of any conspicuous parallelism of the minerals. In general, the metamorphism of a hornstone is less advanced than that of a crystalline schist, and recognizable fossils, even of such delicate organisms as graptolites, have occasionally been found in hornstones.

The width of the metamorphic aureole about an igneous intrusion is variable and depends on many

factors. Large intrusions cause more metamorphism than small ones, and acid eruptive rocks seem to be more effective than basic ones; on the other hand, some sedimentary rocks are more susceptible to metamorphism than others. When different kinds of rock appear successively in the contact zone it will be found that the metamorphic aureole is much wider in slates and limestones than in sandstones or igneous rocks; and when the chemical composition is the same, a porous rock is more strongly affected than a compact one. The shape of the intrusive mass is also important. If it is dome-shaped and dips at a low angle beneath the country rocks then the outcrop of the hornstone zone will be wider than in the case of an intrusion with nearly vertical walls. Again, where the contact surface cuts across the bedding-planes of the country rocks the metamorphic aureole is wider and the metamorphism is more intense than where the contact surface coincides with the structural planes.

CRYSTALLINE SCHISTS

The crystalline schists are the products of recrystallization under directed pressure (stress). When crystals grow under stress the rate of growth is greater at right angles to the direction of stress than in that direction. This is a consequence of the fact that most solids dissolve with diminution of volume, from which it follows that their solubility is increased by pressure; thus the solubility of a crystal which is exposed to stress is greatest in the direction of stress and least in the direction perpendicular to the stress. Conversely, the rate of growth of a crystal under stress is least in the direction of stress and greatest in the perpendicular direction. A pretty demonstration of this was given by F. E. Wright, who prepared cubes of glass having the composition of wollastonite and other silicates and allowed them to crystallize under pressure. When the pressure was applied in one direction only, the crystals were found to be elongated in planes perpendicular to that direction;

when the pressure came from two directions at once, the crystals grew along parallel lines perpendicular to both directions of pressure.

The structures developed in the crystalline schists clearly reflect the influence of stress during their growth. In the commonest case, minerals of a scaly habit such as the micas, chlorites, talc, graphite and hematite, and fibrous or prismatic minerals such as tremolite, actinolite, wollastonite, kyanite, sillimanite and epidote are disposed in parallel planes throughout the rock, indicating one direction of maximum compression. In the rarer case of two stress-maxima the prismatic minerals all lie with their long axes in the direction of least resistance.

The minerals that are most characteristic of the crystalline schists have nearly all got one and sometimes two directions of perfect cleavage. In minerals of a tabular habit the cleavage is parallel to the broad face; in prismatic minerals the cleavage is often parallel to the long axis. Thus the parallel arrangement of the commonest minerals in a schist involves parallelism of their cleavage directions, with the result that all typical crystalline schists split easily into thin leaves which have the lustre of cleavage planes.

The name *gneiss* is given in Germany to the very feldspathic varieties of the crystalline schists. A muscovite- or biotite-gneiss may hold so much alkali-feldspar that except for its foliation it can hardly be distinguished from a granite; indeed, the boundary between the true granites and the granitic gneisses is one of the most indefinite boundaries in petrology. But many gneisses have a streaky appearance due to the dark minerals being largely confined to streaks and lenses (German *Flaser-gneiss*); and others consist of alternating layers of lighter and darker colour, the pale bands being more quartzose, feldspathic or calcareous than the dark bands (German *Lagengneiss*). Some writers, especially in America, restrict the name gneiss to these banded rocks.

In another variety of gneiss some of the constituents

form almond-shaped eyes in a schistose matrix (Eyed-gneiss; German *Augengneiss*). Each eye may be a single crystal of feldspar or garnet but it is more frequently an aggregate. The eyes are in most cases relics of the original structures of the rock; they may have been pebbles in a conglomerate, fragments in a breccia, or insets in a porphyritic igneous rock; but it is not unlikely that some of them, especially the garnet eyes, have been formed by growth in place.

Injection-gneiss or *migmatite* is formed when igneous matter is injected in thin sheets between the beds or laminæ of a sedimentary rock which is concurrently metamorphosed into a schist; or when an eruptive magma incorporates so much metamorphosed sedimentary matter that the mass solidifies with a strongly banded or laminated texture. Injection-gneiss is often developed about the margin of a granite batholith. A zone of injection-gneiss is beautifully exposed on the sea-shore near Cape Town; it was first noticed by Charles Darwin and it is an object of pilgrimage for all geologists who visit South Africa. Injection-gneiss in the north-west Highlands of Scotland is graphically described by Horne and Greenly, and splendid examples have been described by Sederholm in Finland.

Crystalline schists are exposed on a grand scale in all the ancient, relatively stable blocks of the earth-crust, such as Laurentia, Fenno-Scandia, India, Brazil, central and south Africa and western Australia. But metamorphism is not a function of geological age, for there are younger crystalline schists, in no way different from the Archæan ones, which appear in the great mountain chains and can be traced into Paleozoic and Mesozoic sediments outside of the folded region. Silurian trilobites have been found in schists in Norway, Jurassic belemnites in Alpine schists, and brachiopods in garnet-mica schist in New Hampshire. True crystalline schists, as well as hornstones, are developed in the contact zones of many great igneous intrusions.

THE SPECIAL MINERALS OF METAMORPHIC ROCKS

The most abundant minerals of the metamorphic rocks are the same as those of eruptive rocks, namely, quartz, feldspar, muscovite, biotite and hornblende. Garnets are commoner in metamorphic than in eruptive rocks, but pyroxenes are much scarcer. Tourmaline, sphene, zircon, apatite, epidote, corundum, magnetite and hematite are other igneous minerals which reappear in metamorphic rocks.

Of the feldspars, orthoclase or microcline and albite are the commonest, together with microperthite. All members of the plagioclase series may be found but the commonest is oligoclase. Pure anorthite occurs in some lime-silicate hornstones (marmorites). A curious feature of the plagioclase crystals in metamorphic rocks is that when they show a zonal structure the order of the zones is often the reverse of that seen in eruptive rocks, albite predominating in the core and anorthite in the mantle.

The characteristic minerals of metamorphic rocks are summarized below.

(a) *Aluminous group.*

Andalusite, *sillimanite* and *kyanite* are typical products of the metamorphism of argillaceous rocks. All three have the same empirical formula, Al_2SiO_5 , but they differ greatly in appearance and properties. *Andalusite* forms nearly square prisms belonging to the rhombic system and is distinguished under the microscope by its pink to colourless pleochroism. It is particularly common in contact metamorphism, especially the variety called *chiastolite*, which contains carbonaceous enclosures arranged in a cruciform pattern. *Kyanite* forms beautiful blade-like crystals with a fine blue colour; it is only found in crystalline schists. *Sillimanite* forms colourless needles in many hornstones and schists.

Cordierite has the composition $2(\text{Mg}, \text{Fe})\text{O}, 2\text{Al}_2\text{O}_3, 5\text{SiO}_2$. It is common in hornstones and is sometimes found in granite near a slate contact. It often has

a cloudy blue colour but it is in other respects remarkably like quartz and very difficult to distinguish from it. A common microscopic character is the occurrence of yellow haloes around minute enclosures.

Staurolite has the empirical formula $\text{H}_2\text{O}, \text{FeO}, 2\text{Al}_2\text{O}_3, 2\text{SiO}_2$. It forms rhombic prisms and cruciform twins of model-like sharpness. The colour of the crystals is brown; under the microscope they are pleochroic in yellow and red.

Chloritoid belongs to the group of the "brittle micas," which are intermediate in their properties between the micas and the chlorites. The crystals show pleochroism from green to indigo-blue, and are hard enough to scratch glass. The formula of chloritoid may be written $\text{H}_2\text{O}, \text{FeO}, \text{Al}_2\text{O}_3, \text{SiO}_2$.

The *Spinel* family includes ruby spinel, $\text{MgO}, \text{Al}_2\text{O}_3$, which forms pink octahedrons in some crystalline limestones, and pleonaste in which the place of magnesia is taken by ferrous oxide.

Almandine is the name given to the iron-aluminium garnet, $3\text{FeO}, \text{Al}_2\text{O}_3, 3\text{SiO}_2$, which is the common variety of garnet in the crystalline schists and hornstones. The crystals are generally well-developed rhombic dodecahedrons or trapezohedrons, and crystals of large size, even two or three inches in diameter, are not uncommon.

(b) *Calcareous group.*

Grossularite is the lime-alumina garnet $3\text{CaO}, \text{Al}_2\text{O}_3, 3\text{SiO}_2$. It is often formed in lime-silicate hornstones (marmorites). It is usually yellow or pink, but when ferric oxide replaces some of the alumina the colour becomes dark brown (the variety *andradite*).

Vesuvianite is a complicated silicate of lime and alumina, containing also the rare element beryllium. It is often associated with grossularite in marmorites. It crystallizes in tetragonal prisms.

Scapolite is the name of a series of solid solutions between a soda-rich member which is equivalent (in an

arithmetical sense only) to 3 molecules of albite plus one of NaCl, and a lime-rich member which is arithmetically equivalent to 3 molecules of anorthite plus one of CaCO_3 . Scapolite is formed particularly by the metamorphism of plagioclase feldspars and is found in crystalline schists and amphibolites, but also in metamorphosed limestones (marmorites).

Zoisite has the composition $\text{H}_2\text{O}, 4\text{CaO}, 3\text{Al}_2\text{O}_3, 6\text{SiO}_2$. It is a prismatic to fibrous mineral formed by metamorphism of plagioclase. *Epidote* differs from zoisite by having ferric oxide in place of part of the alumina; it is recognized in thin sections by its pleochroism from yellow to colourless.

Wollastonite is simply calcium metasilicate, CaSiO_3 . It is a fibrous to prismatic mineral often formed by the thermal metamorphism of limestone.

(c) *Magnesian group.*

Forsterite or magnesian olivine, Mg_2SiO_4 , is formed by thermal metamorphism of magnesian limestones. It readily takes up water and passes into fibrous *serpentine*, $2\text{H}_2\text{O}, 3\text{MgO}, 2\text{SiO}_2$. The green colour of this mineral is due to a little ferrous oxide replacing part of the magnesia.

Talc is a very soft mineral forming apple-green or silvery scales. The massive form is known as soapstone. Formula $\text{H}_2\text{O}, 3\text{MgO}, 4\text{SiO}_2$.

Chlorite is the name of a group of dark green, micaceous minerals which are the commonest constituents of basic schists. A typical formula is $4\text{H}_2\text{O}, 5(\text{Mg}, \text{Fe})\text{O}, \text{Al}_2\text{O}_3, 3\text{SiO}_2$. Chlorite is distinguished from biotite in thin sections by its very low interference colours.

Tremolite, *actinolite* and *anthophyllite* are fibrous amphiboles. Anthophyllite is $(\text{OH})_2\text{Mg}_7\text{Si}_8\text{O}_{22}$ and tremolite is $(\text{OH})_2\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}$. Actinolite is a bright green variety of tremolite containing ferrous iron.

Brucite is magnesium hydroxide, $\text{Mg}(\text{OH})_2$. It forms soft, silvery scales in some altered dolomites. *Periclase* is magnesium oxide, MgO .

THE CLASSIFICATION OF METAMORPHIC ROCKS.

The study of metamorphism has advanced greatly since **Zirkel's** time, but it cannot be said that there has been any corresponding advance in the systematic treatment of metamorphic rocks. Zirkel's system was simply an enumeration of mineralogical and textural varieties under the general heads of gneiss and schist, or feldspathic and non-feldspathic. The hornstones, quartzites and crystalline limestones were not placed beside the crystalline schists but were described separately in connection with the eruptive rocks that gave rise to them.

Rosenbusch made no advance on this, though he condensed Zirkel's groups into a smaller number of families which show some community of mineralogical or chemical characters. The families of Rosenbusch's system are as follows:—

- (1) The family of gneisses.
- (2) „ „ „ mica-schists.
- (3) „ „ „ talc-schists.
- (4) „ „ „ chlorite-schists.
- (5) „ „ „ amphibole and pyroxene rocks.
- (6) „ „ „ serpentines.
- (7) Rocks of the lime series (metamorphosed limestones).
- (8) Rocks of the magnesia series (metamorphosed dolomites).
- (9) Rocks of the iron series (metamorphosed ironstones).
- (10) Emery.

U. Grubenmann was the first to treat metamorphic rocks on a purely chemical basis. In his book *Die krystallinen Schiefer* (1910) he adopted Osann's method of computing rock analyses (now generally replaced by

Niggli's method, see p. 46) and set up twelve fundamental groups of metamorphic rocks, as follows:—

- (1) Alkali-feldspar gneiss
- (2) Aluminium-silicate gneiss
- (3) Plagioclase gneiss
- (4) Eclogite and amphibolite
- (5) Magnesium-silicate schist
- (6) Jadeite rocks
- (7) Chloromelanite rocks
- (8) Quartzite rocks
- (9) Lime-silicate rocks
- (10) Marbles
- (11) Iron-oxide rocks
- (12) Aluminium-oxide rocks

Within each of these twelve groups three orders were set up which indicate the physical conditions under which metamorphism is believed to have taken place; whether those of the upper, the middle, or the lower zone of the earth-crust. Further subdivision takes place on a mineralogical basis.

In *Die Gesteinsmetamorphose* (vol. 1, 1924), **Grubenmann** and **Niggli** collaborate in a revision and elaboration of Grubenmann's earlier work. The first volume contains a great quantity of new physical and chemical data bearing on metamorphism, and Osann's method of computation is given up in favour of that of Niggli. The second volume is still awaited.

The chemical method of classification has the great practical disadvantage that one cannot think of a rock in terms of the arithmetical proportions of oxides; one can only think in terms of minerals. In the case of eruptive rocks a chemical classification is justified to a certain extent by the existence of hypocrySTALLINE and vitreous rocks which cannot be classified on a mineralogical basis; but with the exception of the pseudo-tachylytes and other rare rocks which have been sintered by heat, all metamorphic rocks are holocrystalline and the great majority

are quite coarse-grained. Grubenmann's twelve groups could be defined just as accurately and far more usefully in terms of minerals instead of oxides.

V. M. Goldschmidt in his great study of *Die Kontaktmetamorphose im Kristianiagebiet* (1911) rightly maintains that "a petrographic system which makes any claim to be a natural system must consider the *actual* mineralogical composition in the first place." Goldschmidt's own procedure is based on the application of the phase rule to the study of metamorphism. This rule tells us that in a system of n components which is stable under variations of temperature and pressure (as all natural rocks are within certain limits) the maximum number of phases that can exist in equilibrium is the same as the number of components. Thus a rock containing only the three components silica, alumina and magnesia cannot hold more than three minerals, provided that equilibrium has been attained. From these three components the following phases (minerals) can be formed: quartz, corundum, periclase, andalusite, enstatite, olivine, spinel, cordierite. Sets of three minerals can be chosen in a large number of ways, but certain associations are incompatible; for instance

quartz + corundum	= andalusite
quartz + periclase	= enstatite or olivine
enstatite + periclase	= olivine
olivine + quartz	= enstatite
corundum + periclase	= spinel
spinel + quartz	= cordierite
olivine + andalusite + quartz	= cordierite
enstatite + andalusite + quartz	= cordierite

When all such cases have been eliminated, there remain as possible combinations of the eight minerals named above only the following:—

- (1) olivine, andalusite, cordierite
- (2) andalusite, quartz, cordierite

- (3) enstatite, quartz, cordierite
- (4) enstatite, andalusite, cordierite
- (5) enstatite, olivine, cordierite
- (6) enstatite, olivine, andalusite.

But in all common varieties of shale and slate there is an abundance of quartz, so the systems containing olivine are excluded in practice. Case 4 also becomes impossible if quartz is added, for then the number of phases exceeds the number of components; the reaction $\text{enstatite} + \text{andalusite} + \text{quartz} = \text{cordierite}$ sets in until either enstatite or andalusite is used up and there remains only $\text{andalusite} + \text{cordierite} + \text{quartz}$ or $\text{enstatite} + \text{cordierite} + \text{quartz}$. Since most shales and slates hold more alumina than magnesia, it is chiefly the combination $\text{andalusite-cordierite-quartz}$ that occurs in nature.

If soda is added to the components it combines with part of the alumina and silica to form albite, thereby reducing the quantity of andalusite and quartz. If potash is added it may form either orthoclase or muscovite, the latter using up relatively more alumina. Potash can also bind magnesia in the form of biotite. With the addition of lime the matter becomes still more complicated, and it is only by making a number of simplifying assumptions of doubtful validity (for instance, ignoring the presence of combined water and considering $(\text{Mg}, \text{Fe})\text{O}$ as a single component) that Goldschmidt is able to establish his contention that all the possible types of hornstone that can be formed from more or less calcareous clay-slates fall into the following groups (which are arranged in order of increasing CaO):—

- (1) Quartz-biotite-andalusite-cordierite-albite hornstone.
- (2) Quartz-biotite-andalusite-cordierite - plagioclase hornstone.
- (3) Quartz-biotite-cordierite-plagioclase hornstone.
- (4) Quartz - biotite-cordierite - plagioclase - hypersthene hornstone.
- (5) Quartz-biotite - plagioclase - hypersthene hornstone.

- (6) Quartz-biotite-plagioclase - hypersthene - diopside hornstone.
- (7) Quartz-biotite-plagioclase-diopside hornstone.
- (8) Grossularite-plagioclase-diopside hornstone.
- (9) Grossularite-diopside hornstone.
- (10) Grossularite-wollastonite - vesuvianite - diopside hornstone.

To the above types, which are mostly quartz-bearing, C. E. Tilley adds the following silica-poor assemblages, all of which are realized in nature:—cordierite-andalusite-spinel, cordierite-enstatite-spinel, corundum - cordierite-spinel, corundum-spinel-andalusite (or sillimanite or kyanite), corundum-cordierite-andalusite (or sillimanite or kyanite).

The method of Goldschmidt undoubtedly holds the germ of a rational classification of metamorphic rocks, but its extension to the crystalline schists presents an immensely difficult problem.

P. Eskola (1915, 1921). Since the character of a metamorphic rock must vary according to the intensity of the factors causing metamorphism, Eskola introduced the concept of *metamorphic facies*, which he explained in these words: a metamorphic facies includes rocks which may be supposed to have been metamorphosed under identical conditions. For example, an argillaceous rock of definite chemical composition may give rise, under one set of conditions, to an andalusite schist, and under another set of conditions, to a sillimanite schist; these products belong to different metamorphic facies. On the other hand, two rocks of different chemical composition, such as a slate and an impure limestone, if metamorphosed under identical conditions, may form respectively a quartz-cordierite-andalusite hornstone and a grossularite-vesuvianite-diopside rock; and these very different end-products belong to the same metamorphic facies.

In his latest discussion of the facies principle, Eskola described eight important metamorphic facies which he called the sanidinite facies, the hornfels facies, the amphi-

bolite facies, the epidote-amphibolite facies, the green-schist facies, the granulite facies, the eclogite facies, and the glaucophane-schist facies. Space does not permit us to describe the characters of these facies, but something may be gathered from their names. There is no doubt that the concept of metamorphic facies is important, but it does not by itself furnish a classification of rocks, since, as we have seen, a single facies may embrace rocks of very different mineralogical composition. Eskola recognized this and said that "the most natural nomenclature in the facies system would be one where every rock name would be composed of two parts, the former representing the typical mineral constituents and the latter the facies." No such nomenclature has yet been elaborated.

British petrologists have used the term *metamorphic grade* rather than facies, and have preferred to characterize each grade by a single mineral rather than a rock type. Thus in the Highlands of Scotland it has been possible to distinguish the following metamorphic grades in a series originally composed of argillaceous sediments: chlorite grade, biotite grade, almandine grade, staurolite grade, kyanite grade, sillimanite grade; the last representing the highest grade of metamorphism.

N. L. Bowen has shown that in the thermal metamorphism of siliceous limestone and dolomite, the following ten minerals succeed one another with rising temperature: tremolite, forsterite, diopside, periclase, wollastonite, monticellite, akermanite, spurrite, merwinite, larnite.

In these studies one sees the germ of a genetic classification of metamorphic rocks, but it will be long before the details can be worked out.

The system used in this book. In the following chapter we shall describe the metamorphic rocks under the three headings of (1) mylonites, (2) hornstones, (3) crystalline schists. In view of the very large number of mineral associations that occur among the crystalline

schists we must adopt some rational method of subdividing that group. In the first edition of this book the writer tried the experiment of reducing the crystalline schists to four types based on the molecular ratio of alumina to other basic oxides, as he had already done in the case of the eruptive rocks. But adherence to an arbitrary set of ratios introduced certain discrepancies between the types set up on this basis, among the eruptive rocks, and those suggested for the crystalline schists, although the same names were used in each case. These discrepancies relate especially to the minerals biotite, tourmaline, and hornblende, in each of which the alumina ratio is extremely variable. It seems advisable to make a small adjustment of the system in order that these minerals may have the same significance, from the point of view of classification, whether they occur in eruptive rocks or in metamorphics.

The four types of crystalline schist which it is proposed to recognize are:—

The *peraluminous* type. The possible minerals are the same as in the peraluminous type of eruptive rocks, that is, corundum, muscovite, biotite, tourmaline (but not the almandine-spessartite garnets, which are of negligible importance in eruptive rocks); with the addition of the metamorphic minerals andalusite, sillimanite, kyanite, staurolite, dumortierite. In these minerals the molecular ratio of alumina to other basic oxides is greater than 1 : 1, with biotite as an exception.

The *metaluminous* type. Possible minerals are the aluminous amphiboles, epidote, and melilite, with the addition of cordierite, chloritoid, scapolite, zoisite, chlorite, and the garnet group. The molecular ratio of alumina to basic oxides, in these minerals, ranges from 1 : 1 to 1 : 5, but is usually less in hornblende. To this type we may also attach those rare rocks which contain a peraluminous mineral together with a subaluminous mineral, as kyanite with pyroxene, corundum with anthophyllite. These associations probably indicate failure to attain equilibrium.

The *subaluminous* type. Possible minerals are the ortho- and clino-pyroxenes and olivine, with the addition of the non-aluminous amphiboles (anthophyllite, actinolite, etc.), talc, serpentine, and magnesite. Alumina is absent or negligible.

The *peralkaline* type. The characteristic minerals of this rare type of rock are jadeite, and glaucophane, in which alumina is combined with soda.

These four types of rock are not sharply separable; for example, a peraluminous schist may contain a minor quantity of a mineral of the metaluminous group, as sillimanite-garnet gneiss; and a metaluminous schist may hold a little of a subaluminous mineral, or vice versa, as in the case of a garnet-enstatite rock. In spite of this defect, the separation of these four types of crystalline schist is a step in the direction of bringing together rocks of similar chemical character.

SUGGESTIONS FOR READING.

- T. J. JEHU and R. M. CRAIG, *The Geology of the Outer Hebrides*. Trans. Roy. Soc. Edinburgh, vol. 53, pp. 430 and 627; vol. 54, p. 483; vol. 55, p. 483.
- S. J. SHAND, *The Pseudotachylyte of Parijs, Orange Free State*. Quart. Jour. Geol. Soc., 1917, p. 198.
- F. E. WRIGHT, *Schistosity by Crystallisation*. Amer. Jour. Sci., vol. XXII., 1906, p. 224.
- A. HARKER, *Metamorphism* (London, 1932).
- J. JOHNSTON and P. NIGGLI, *The General Principles underlying Metamorphic Processes*. Jour. Geol., 1913, pp. 481 and 588.
- P. ESKOLA, *The Mineral Facies of Rocks*. Norsk. Geologisk Tidsskrift, vol. 6, 1921.
- C. E. TILLEY, *The Facies Classification of Metamorphic Rocks*. Geological Magazine, vol. 61, 1924, p. 167.
- A. C. WATERS and C. D. CAMPBELL, *Mylonites from the San Andreas Fault Zone*. Amer. Journal of Science, vol. 29, 1935, p. 473.

CHAPTER XV.

METAMORPHIC ROCKS—DESCRIPTION

CLASS I—MYLONITES.

When a massive rock yields to stress the first result is the production of a network of cracks which intersect at high and low angles. The cracks themselves are partly occupied by pulverized rock, and in the meshes of the network the blocks of rock are uncrushed and angular in shape. If the strain is fully relieved, matters will remain like this with the exception that in course of time the cracks will be healed by introduction of silica or some other cementing material. The rock is now a fault breccia. If further movement takes place, the angular blocks will gradually be reduced by abrasion, the proportion of rock powder will be increased, and the boulders may become rounded or spindle-shaped. A rock in this stage of crushing is sometimes called a crush-conglomerate. If movement still goes on the boulders will be broken up more and more, but some of the tougher fragments will survive as eyes or lenses in the crushed matrix, and the matrix itself will gradually change its character in one of two possible ways. Either it will begin to recrystallize, developing scales of mica and chlorite in the planes of movement until the rock has the character of a crystalline schist; or it will be milled down to finer and finer grain, with development of heat, until the rock becomes compact and flinty or semi-vitrified, forming a flinty crush-rock or a pseudo-tachylyte.

Flinty crush-rock, as its name suggests, is compact and flint-like and its true nature may be quite unrecognizable in the lump. Under the microscope it is seen to

be composed of a highly compacted rock dust. The larger fragments are of quartz or feldspar and they may be angular or rounded; the smaller fragments form a streaky matrix of quartz, feldspar, biotite, hornblende, etc., which flows around the larger ones. In a typical flinty crush-rock there is no sign of melting; but if much heat is developed by friction then the grains become welded together to form the structureless and nearly isotropic material that has been called pseudo-tachylite. The rock to which this name was first given in the Orange Free State is a dense, black material full of irregular scraps of quartz and feldspar and larger, well rounded lumps of granite. Under the microscope the base polarizes in very dull greys, and different parts extinguish in different positions, but no distinct structure can be recognized and there is no resemblance to a powder. The dark colour is due to a multitude of minute specks of magnetite which have been liberated by decomposition of biotite. The larger fragments of quartz and feldspar are much cracked, the quartz grains in particular showing a minute mosaic structure between crossed nicols, and their margins have a fretted appearance as if they had been corroded by the matrix. Some of the feldspar grains fade away into streaky, cloud-like patches which seem to indicate actual melting of feldspar. Here and there are signs of recrystallization in the matrix, leading either to swarms of tiny green prisms which seem to be hornblende or else to spherulites and microlites of feldspar.

The pseudo-tachylite of the Outer Hebrides repeats every feature of the South African rocks, including the half-melted feldspar grains, the powdery magnetite, and the occasional development of spherulites and microlites of feldspar. The veins in the "trap-shotten gneiss" of Madras are described by Holland as an indurated black dust through which fragments of quartz and feldspar are disseminated; they seem to be less completely welded than the pseudo-tachylites described above.

The mylonites of the San Andreas fault zone exhibit every stage of crushing, from a coarse breccia down to an ultramicroscopic powder with "eyes" of feldspar. Rarely the groundmass is almost isotropic and then it shows flow structure and resembles volcanic glass; but the refractive index of this material is always higher than that of Canada balsam, whereas a true glass produced by melting the powdered rock in the crucible has an index of only 1.53. Examination of pseudo-tachylite with X-rays indicates the presence of minute crystalline grains but does not positively disprove the presence of a little interstitial glass.

CLASS II—HORNSTONES, QUARTZITES AND MARMORITES.

These rocks are products of thermal metamorphism. Hornstones are formed especially from claystones but also from tuffs and lavas; quartzites from sandstones, and lime-silicate rocks (marmorites) from limestones and dolomites.

There is no justification, on mineralogical grounds, for separating the hornstones from the crystalline schists, for no mineral is found in hornstones that does not also occur in schists. The main difference between the two classes of rocks is a textural one, typical hornstone being a fine-grained or dense rock requiring the microscope for its study, while most schists and gneisses are so well crystallized that all the important constituents can be identified with the naked eye. Another point of difference is the general absence of schistosity in the case of hornstones. If a certain degree of parallelism is observed among the mica scales in a hornstone, this is more probably a relic of the lamination of the original claystone than a sign of crystallization under stress. In short, the hornstones as a class show a lesser degree of recrystallization (lower grade of metamorphism) than the crystalline schists, and it is often possible to recognize in the field, at no great distance, the unaltered rock from which the hornstone was formed.

The hornstones are dark grey, often somewhat lustrous rocks, usually without fissility or lamination, breaking with an irregular, splintery fracture. Most of them are fine-grained, the average size of the particles being only one or two tenths of a millimetre. Under the microscope such a rock is seen to be made up of grains of uniform size which interlock closely and seldom show any crystalline form. The grains are typically poikilitic or sieve-like, that is, they are crowded with little enclosures which produce the appearance of holes in a sieve. These characters, taken together, constitute typical "hornstone structure." But there is another type of hornstone which is strongly porphyritic, certain minerals, of which andalusite is the commonest, forming isolated, well shaped crystals many times larger than the average grain of the rock. It is not known what is the cause of porphyritic texture, but Goldschmidt remarks that the largest insets of andalusite and cordierite are found in rocks that contain much carbonaceous matter.

A very common constituent of hornstones is quartz, in interlocking grains that show sieve-structure. Orthoclase is also poikilitic and lacking crystal form, but plagioclase may be idiomorphic, especially if it is enclosed in quartz. Biotite of a brown colour is another very common constituent, often making up a third of the rock. It forms little tables and scales which may be poikilitic or nearly free from enclosures. Andalusite forms either shapeless, poikilitic grains or larger prisms which give lath-shaped sections parallel to their length and rhomboidal cross-sections. Pleochroism is generally recognizable in some parts of the crystals. The large insets of andalusite may be several centimetres long and they contain carbonaceous enclosures (chistolite). Cordierite forms shapeless or rounded grains; they are distinguished from quartz grains by the presence of minute enclosures about which there are yellow pleochroic haloes, and by the twinning which becomes apparent when the nicols are crossed. Each crystal is a penetration trilling, and the

different segments extinguish in different positions. Pyroxenes and amphiboles (diopside, hypersthene and green or brown hornblende) occur in the less common kinds of hornstone; they tend to form idiomorphic prisms and grains which enclose quartz. Tourmaline is a common accessory mineral in many hornstones, especially close to the contact with granite; and magnetite and rutile are almost always present. Scales and dust-like grains of graphite are enclosed in great numbers, especially in andalusite and cordierite.

The hornstones developed about the little granite stock of Barr-Andlau in the Vosges Mts. have become classic since their description by Rosenbusch in 1877. The stock, which measures five kilometres by four, cuts a series of clay-slates with subordinate limestone and graywacke, and the zone of contact metamorphism varies from 100 to 1,200 metres wide. The clay-slate has been altered to spotted slate and chistolite slate, and with closer approach to the granite it loses its fissility and passes into massive, fine-grained andalusite-hornstone, containing in addition to andalusite, quartz, white and brown mica, magnetite and hematite. The andalusite is mostly in microscopic prisms but is sometimes porphyritic. Cordierite-sillimanite hornstone is also developed in the neighbourhood, and a tourmaline-staurolite variety too; and the limestones have been changed to garnet-pyroxene marble.

Another famous granite-hornstone contact is that at Crawford Notch, New Hampshire, which was described by Hawes in 1881. The chief variety of hornstone is a compact, black rock riddled with crystals of andalusite several inches long. This mineral is not present in the groundmass, which consists of quartz, muscovite, chlorite, magnetite and graphite. Near the margin of the granite, tourmaline becomes the most important constituent of the hornstone.

Admirable descriptions of hornstones of every kind have been given by Brögger and Goldschmidt from the

Christiania (Oslo) district of Norway. The andalusite-cordierite hornstone of Gunildrud is porphyritic, holding large prisms of andalusite (chiastolite) in a fine-grained groundmass consisting of quartz, feldspar, cordierite and biotite. White mica is present, too, but it is a secondary product formed by alteration of cordierite. Apatite and rutile are accessory, and the groundmass is full of specks of graphite. Goldschmidt gives the mineralogical composition of this rock as follows:—

Potash felspar (in round numbers)	35
Albite	10
Quartz	21
Andalusite	7
Cordierite	14
Mica	6
Rutile, apatite, pyrrhotite, graphite	6

As an example of a plagioclase-bearing hornstone we may quote the rock described by Goldschmidt from Sölvbergerget; it is the metamorphic product of a rather calcareous and magnesian clay-slate. The rock is dark grey, with little insets of potash-feldspar a few millimetres long and many tiny scales of biotite. In thin section the following minerals are seen: hypersthene, in prisms about a millimetre long; laths of labradorite, often enclosed in orthoclase; much quartz, and a few grains of diopside, apatite, zircon and graphite. The calculated composition is

Quartz	14
Potash feldspar	10
Plagioclase	37
Hypersthene	15
Biotite, etc.	25

If the initial rock is a sandy claystone or clayey sandstone the product of thermal metamorphism will be a rather quartz-rich hornstone. From a purer sandstone one will get a still more siliceous hornstone, and in an extreme case the product will be a simple *quartzite* consisting entirely of interlocking grains of quartz which have lost

every trace of their clastic origin. Such a quartzite, which will not be different in appearance from those discussed in Chapter XII, is just a special variety of hornstone. Since no sandstone consists wholly of quartz, most quartzites hold some grains of clear recrystallized feldspar and generally a few scales of white or brown mica and some magnetite. A trace of clayey matter in the sandstone may be changed into needles of sillimanite or a few pink garnets.

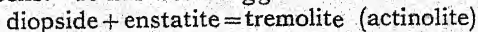
A pure limestone, if nothing is added to it during metamorphism, can only be changed by recrystallization, giving a *marble*. But many limestones contain admixtures of clay and sand, and solutions escaping from an invading magma may introduce ferric oxide, silica and other compounds into the rock. In the *marmorites* (lime-silicate hornstones) there is consequently a large development of lime, lime-alumina, and lime-ferric silicates such as anorthite; grossularite and andradite; wollastonite, diopside and hedenbergite; vesuvianite, scapolite, sphene, apatite; and in highly magnesian limestones forsterite, chondrodite, phlogopite, tremolite; as well as periclase, brucite, and spinel. Contributions from magmatic sources are indicated by an abundance of iron minerals, especially andradite, magnetite and hematite, and by the presence of minerals containing fluorine, chlorine, phosphorus, boron or sulphur, for example, vesuvianite, scapolite, apatite, axinite and sphalerite. Iron-rich contact rocks are known in Scandinavia as *skarn* (originally a miners' term meaning rubbish). Graphite is quite a common accessory mineral in marbles and marmorites.

Along with the silicates in marmorites there may be large or small quantities of recrystallized calcite, and quartz is also a possible constituent. Whether calcite and quartz occur together or not depends on the temperature and pressure prevailing in the contact-zone; if the temperature exceeds five or six hundred degrees the two minerals combine to form wollastonite. Since mag-

nesium carbonate gives up CO_2 at a much lower temperature than calcium carbonate, the first minerals to form, in the thermal metamorphism of a more or less magnesian limestone, are the magnesian minerals phlogopite, forsterite, periclase, tremolite, and diopside. High grade metamorphism is indicated by wollastonite, monticellite, and the rare larnite or calcium orthosilicate.

The texture of the marmorites is typically allotriomorphic, and sieve-structure is almost universal. Diopside grains enclosed in calcite are rounded and drop-like, and have a high lustre. Garnets are more successful than other minerals in developing their proper crystalline form; they may be dodecahedrons or trapezohedrons, and they generally carry enclosures of diopside or calcite. Sometimes what seem to be stout crystals of garnet are mere shells of garnet-substance filled with calcite. Goldschmidt has described a rock from the Christiania district which appears to be made up entirely of large dodecahedrons of garnet, but when it is examined under the microscope every crystal is found to be filled with diopside grains arranged in regular zones. The garnet of marmorites is very often manganiferous, a well-known instance being the beautiful pink garnets of Morelos State, Mexico, which are associated with yellow vesuvianite. It is noteworthy that magnesian and ferrous garnets (pyrope, almandine) are not found in marmorites, the molecules of magnesia and ferrous oxide going principally into diopside. For the formation of vesuvianite it is necessary that water should be present. Goldschmidt finds that the association grossularite-wollastonite-vesuvianite is common but the grossularite-wollastonite association without vesuvianite is very rare.

An amphibole takes the place of pyroxene in some of these rocks. It has been suggested that the reaction



is promoted by high pressure; but as all pyroxenes are denser than the corresponding amphiboles this explanation is unlikely. Amphibole-production seems to be

favoured in general by moderate temperature and hydrous conditions rather than by high pressure.

Characteristic mineral associations in marmorite and skarn are calcite-diopside, calcite-tremolite, calcite-forsterite (passing over into calcite-serpentine), calcite-brucite; calcite-grossularite-diopside, grossularite-wollastonite-vesuvianite, calcite - andradite-magnetite, hedenbergite-andradite-magnetite.

CLASS III—THE CRYSTALLINE SCHISTS.

The members of this great class of rocks are distinguished from sedimentary rocks by their highly crystalline character, and from eruptive rocks partly by their texture and partly by the occurrence of minerals such as kyanite and staurolite which are not stable under magmatic conditions. The characteristic texture of the crystalline schists is a foliation imparted by the parallel arrangement of prismatic, scaly and tabular crystals throughout the rock; this is combined with the property of easy cleavage in the direction of foliation. But a schistose texture is only developed in rocks which crystallized under stress; in the less common case of hydrostatic pressure the minerals have no special orientation and the texture is similar to that of a hornstone or marmorite. Schistosity is always inconspicuous in rocks that consist very largely of feldspar and quartz with hardly any of the scaly or prismatic minerals. Some of the so-called granulites of Saxony are fine-grained gneisses composed of feldspar, quartz and a few garnets; in these there is hardly a sign of schistosity, and without field evidence it would be very hard to distinguish such a rock from an aplite. In the field, however, the garnet-granulites are found to pass gradually into mica-granulites with distinct schistosity, and other members of the same suite of rocks hold kyanite or sillimanite, so the metamorphic character of the complex as a whole is put beyond doubt. The final test of eruptive or metamorphic origin is always the field evidence.

When recrystallization takes place in a solid rock, the new growths do not necessarily make their appearance in a definite order as they do from a fluid magma. It is often difficult to determine the order of crystallization in an eruptive rock, but it is still more so in a metamorphic one for the reason that only those minerals that are possessed of an unusually strong crystallizing power, such as garnet and staurolite, have succeeded in developing distinct crystal-form. The largest grains, which might be thought to have crystallized first, are often riddled through and through with minute enclosures of the other minerals (sieve-structure) and must therefore have crystallized after these. In eruptive rocks one often sees that the enclosures of one mineral in another are arranged in zones parallel to the crystal faces of the host; but in metamorphic rocks two minerals will grow right through each other like the differently coloured threads in a carpet, each keeping its own orientation without regard to the other. Thus neither the size nor the shape of the grains, nor the enclosures of one mineral within another, gives any clear indication of the sequence of crystallization.

In the pages that follow we shall discuss the crystalline schists under the headings of peraluminous, metaluminous, subaluminous and peralkaline, as defined on page 196.

Peraluminous Type.

Peraluminous schists and gneisses are exceedingly common. The most conspicuous constituent is generally some kind of mica, either muscovite or biotite or rarely the soda-mica paragonite. If the rock is poor in mica the scales will be isolated, as in many gneisses, but in most of the peraluminous schists the mica is so abundant that it forms continuous films throughout the rock; thus on looking at a cleavage surface one gets the impression that the whole rock is composed of mica, and it is only on examining the cross fracture that one recognizes the

presence of quartz or feldspar. Muscovite is commoner than biotite, but an intergrowth of both kinds is perhaps commonest of all. An emerald-green chrome-mica is found in some cases.

Quartz is a large constituent of all these rocks, in the form of grains, lenses, rods, and sometimes of thin films which alternate with films of mica. No trace of crystal form is ever recognizable, and the larger areas of quartz are aggregates, not single crystals. The feldspar may be orthoclase or microcline, microperthite, albite or oligoclase, just as in granite. It is unusual for the feldspar grains to show crystal faces, though the larger ones may do so. The presence of large crystals of feldspar in a more fine-grained groundmass produces a porphyritic gneiss, or "eyed gneiss" as it is generally called. When andalusite, kyanite, staurolite or corundum is present in a schist or gneiss it often forms crystals which are much larger than the average grain of the rock. Andalusite prisms may be two or three inches long, and corundum, kyanite and staurolite also form large, well-shaped crystals. Round about these large crystals the groundmass of the rock tends to be quite free from the mineral in question.

Many schists and gneisses carry nothing but quartz, feldspar and white or black mica, with a few scattered garnets or grains of tourmaline and rutile. After these simple granitic types, the andalusite-mica schists and gneisses are commonest. The rock of Bodenmais, Bavaria, which holds big prisms of pink andalusite in a base of silvery mica-schist, is a typical example and is to be seen in all mineralogical collections. If andalusite is less abundant than it is in this case, it forms irregular grains in the micaceous network of the schist. It is often accompanied by staurolite or garnet, rarely by sillimanite. The latter mineral is polymorphous with andalusite and kyanite, and of the three sillimanite is the high-temperature form. It is unusual for polymorphous substances to occur together, and when it happens one of them must be unstable.

Fine examples of sillimanite-gneiss have been described from the Ross of Mull, Scotland. The sillimanite forms apparent prisms up to an inch in length, but each prism is seen under the microscope to be in reality a bunch of very thin needles in nearly parallel position. The other minerals of this rock are muscovite and biotite, with or without some garnets. Under the microscope cordierite, andalusite, spinel and apatite are detected. Kyanite-gneiss, containing prisms of blue kyanite up to three inches long, is found in the same region. Excellent examples of sillimanite-, kyanite-, and staurolite-gneisses in north-eastern Scotland were described by G. Barrow in an important paper which the student should read. The most widely-known example of a kyanite-staurolite rock is no doubt the paragonite-schist of the St. Gotthard region in the Lepontine Alps. The beautiful blue kyanite prisms and the cruciform twins of staurolite, standing out from a background of silvery paragonite, are to be seen in every mineralogical museum.

Staurolite, sillimanite, and kyanite schists are splendidly developed in the Littleton formation (Devonian) of New Hampshire, and in Connecticut. Crystals of staurolite 3 to 4 inches long occur about Mascoma Lake and near Littleton. Sillimanite forms large crystals, many of which are sheaves of thin needles, in the Cardigan, Littleton, and Monadnock Quadrangles. The Cob Hill schist contains an average of 20 per cent. of sillimanite, with quartz, feldspar, one or both micas, and garnets. A schist with large blades of blue kyanite occurs near Berkhamstead, Connecticut.

The appearance of corundum in a schist or gneiss indicates an extraordinary richness in alumina. Corundum-mica schists have been described in Connecticut and at Kinta, in the Federated Malay States; and a corundum-mica gneiss has been mined in Gallatin Co., Montana. Some striking corundum rocks are found in the north-eastern Transvaal. One of these consists of plates

of pink corundum embedded in massive sillimanite; another contains blades of sapphire-blue kyanite in association with pink corundum and an emerald-green mica. Corundum-kyanite rocks are also reported at Litchfield, Connecticut, and a mica-schist containing corundum, andalusite, kyanite and chloritoid at Bull Mtn., Virginia. Corundum-tourmaline rocks containing spinel and mica occur at Kinta, Federated Malay States, and a rock composed of blue corundum, mica, rutile and tourmaline in the Serra de Itaquí, Brazil.

Tourmaline is a common accessory mineral in schists, but seldom a major constituent. It is found especially in proximity to igneous intrusions, and as it contains boron and fluorine—two elements which are not normally present in any quantity in sedimentary rocks—it is likely that the production of tourmaline is due to emanations from the magma even more than to rising temperature.

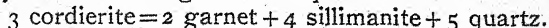
Genesis of peraluminous schists. The purely micaceous type of schist or gneiss may be formed by the metamorphism of a granite or an arkose; but those that carry andalusite, kyanite, staurolite, cordierite or corundum have such a high content of alumina as to make it almost certain that they were formed by the metamorphism of claystones, for no other kind of rock except the rare corundum-pegmatites holds anything like such a great excess of alumina over the bases. This conclusion can often be backed by field evidence, where the sillimanite-kyanite-staurolite gneisses are interbedded with quartzites and crystalline limestones.

Metaluminous type.

In the characteristic minerals of this type of rock there is no excess of alumina over the basic oxides, of which magnesia is the most abundant. The highest proportion of alumina is present in cordierite and chloritoid, also in spinel; in these species $\text{Al}_2\text{O}_3 : (\text{Mg}, \text{Fe})\text{O} = 1 : 1$.

Cordierite is not a typical mineral of the crystalline schists. It is never observed in strongly foliated rocks,

but appears now and then in the coarser feldspathic gneisses which show little effect of shearing stress; for this reason cordierite is held to be an "anti-stress" mineral. Under severe stress, the components of cordierite are probably shared between garnet and sillimanite or kyanite according to the equation



In cordierite-gneiss, biotite is the commonest dark mineral and the composition of the rock approaches that of biotite-granite. At Bodenmais, Bavaria, there is a well-known cordierite-gneiss containing orthoclase, oligoclase, quartz and biotite, with a little almandine, tourmaline, and graphite. The latter mineral is rather a common accessory in cordierite rocks. A coarse-grained cordierite-gneiss occurs near Guildford, Connecticut. The cordierite is not uniformly distributed but is confined to the more feldspathic bands; it is full of tiny inclusions surrounded by the characteristic yellow haloes.

Chloritoid (ottrelite) characterizes a minor group of schists and phyllites. The crystals are hexagonal tables, usually less than a millimetre in diameter, but crystals of several grams in weight occur in a sillimanite-gneiss in Ile de Groix, France. Large crystals of chloritoid also occur in association with kyanite at Kosoibrod, Ural Mts., and with corundum and kyanite at Bull Mtn., Virginia.

Garnet-rich gneiss and schist are extremely common in all regions of highly metamorphic rocks. The garnet always belongs to the almandine variety and is pink or brown in colour. The larger crystals show the faces of the dodecahedron or trapezohedron; the smaller ones are mostly rounded. A typical example of a garnet-rich gneiss is the "kinzigite" of the Black Forest. This rock shows closely packed grains of red garnet in a groundmass of brown biotite with oligoclase and relatively little quartz. Sillimanite is sometimes present along with a little muscovite, and green grains of spinel (pleonaste) can be detected under the microscope.

The chlorite-schists are an important group, distinguished by their dark green colour and by a slightly greasy feeling when chlorite is abundant. There are several varieties of chlorite which differ considerably in their composition and optical properties; besides this, the scales of chlorite may be intergrown with talc, biotite or hornblende. This is typically a group of dark schists, for although quartz and feldspar are generally present they are quite subordinate in amount to the dark minerals. The rather scanty feldspar is mostly albite. Other dark minerals which are commonly associated with those already mentioned are epidote, garnet, magnetite and graphite. Good dodecahedral crystals of garnet occur in chlorite-schists in the Tyrol, and large octahedrons of magnetite are common in the Alps and elsewhere. In drusy cavities among the chlorite-schists of the Alps beautiful crystals of albite, sphene, epidote and other mineral species are found.

Under the microscope a chlorite-schist shows a confused aggregate of green, pleochroic scales of chlorite, in the interstices of which one recognizes occasional grains or lenses of albite, quartz, epidote and magnetite.

Biotite-hornblende gneiss, which generally carries some garnets, is often interbedded with ordinary biotite-gneiss, for instance, in the St. Gotthard tunnel. With the coming in of hornblende, plagioclase begins to predominate over orthoclase, just as it does in eruptive rocks, and sphene appears in notable quantity. The hornblende is green in thin section and it may be intergrown with a green or colourless pyroxene or chlorite or epidote. Rutile, magnetite, apatite and zircon are common accessory minerals.

A typical hornblende-gneiss is a well banded rock made up of dark layers which are rich in black hornblende needles and paler layers in which quartz, feldspar and garnet predominate. Hornblende may be the only dark mineral but it is very often associated with pyroxene and some biotite or epidote. The feldspar includes both

orthoclase and oligoclase. Under the microscope the hornblende crystals become green or brown, and they are generally spongy with enclosures of other minerals. Pyroxene and hornblende or epidote and hornblende are often intergrown.

Amphibolite is a schistose or massive aggregate of interlocking hornblende needles. A red garnet is a frequent accessory mineral in these rocks; it is probably a magnesium-calcium garnet, for it has been observed to alter into chlorite and epidote. The garnets sometimes act as centres round which the hornblende crystals group themselves radially. Chlorite is often present in hornblende schists and amphibolites; so is talc, and a little biotite is not unusual. Epidote or zoisite may be expected; the latter is formed at the expense of plagioclase feldspar, so when zoisite is present plagioclase is generally excluded. Sphene and magnetite are always to be found.

The passage of dolerite (diabase) into hornblende-schist was studied by J. J. H. Teall in the north of Scotland. The dolerite is a typical coarse-grained dyke-rock consisting of augite and labradorite in ophitic intergrowth, with titanomagnetite and some secondary green hornblende. In places this rock passes by imperceptible gradations into a lustrous, strongly foliated schist which is built up of bands of more hornblendic and more feldspathic character. The constituents of the schist are green hornblende, quartz, albite, iron ore, sphene and apatite. Other instances of the derivation of hornblende-schist from dolerite or basalt are known, and they make it likely that most occurrences of schistose hornblende rocks have the same origin.

The Manhattan schist series, on which the city of New York is built, consists for the most part of biotite-muscovite schist and gneiss, often full of garnets. Certain bands carry staurolite, tourmaline, sillimanite or kyanite. Interbanded with these peraluminous rocks are thick beds of hornblende gneiss which can be followed for thousands of feet along the strike and are very rarely transgressive. The following range of composition is typical: quartz

15 to 30, orthoclase up to 35, oligoclase 10 to 20, hornblende 30 to 50 per cent., with a minor content of garnet and epidote. The composition and the occasional transgressive attitude of these hornblendic rocks suggest that they were originally basic intrusions (and perhaps extrusions) among the argillaceous rocks which were converted into Manhattan schist.

Epidote and zoisite seldom play the main part in gneiss or schist; they are generally subordinate to biotite, chlorite or hornblende. An epidote-biotite schist occurs at Greiner in the Tyrol; it carries twenty per cent. of epidote and seventy of biotite, the remainder being quartz and albite. A chlorite-epidote schist containing large insets of urallite (pseudomorphs of hornblende after augite) has been described at Ekaterinburg in the Ural Mts.

Genesis of the metaluminous type. It is difficult to make any generalization about the rocks of this comprehensive group. The cordierite- and the garnet-bearing facies may have been derived from argillaceous sandstones. The hornblende-biotite-epidote facies probably represent intermediate and basic eruptive rocks and tuffs. The chlorite-schists may have various origins, but some are known to be metamorphosed eruptive rocks. Chloritoid is formed from sedimentary rocks rich in ferrous oxide.

Subaluminous type.

Pyroxene-gneiss is relatively scarce, for the pyroxenes tend under shearing stress to be transformed into amphiboles. There is, however, a group of "pyroxene granulites," relatively fine-grained rocks with an aplitic texture and little trace of foliation, in which both ortho- and clino-pyroxenes are developed. The associated minerals include quartz, orthoclase, plagioclase, garnet, and rarely kyanite. Both in texture and in mineralogy these rocks resemble hornstones rather than crystalline schists, but they are not found in contact metamorphic aureoles. The "charnockite series" of India, Ceylon, and East Africa

is another group of this character. These rocks range in composition from hypersthene-granite to norite and pyroxene, but the characteristic textures of eruptive rocks are lacking. The members of the charnockite series are medium to fine-grained, non-porphyritic, and the grains are allotriomorphic and remarkably uniform in size, as in hornstones. The noritic members only rarely show ophitic texture. Schistosity is almost lacking, but there is often a distinct lineation. It is generally believed that these rocks are of eruptive origin, but that they have been recrystallized under high pressure with little shearing stress.

Since all pyroxenes are denser than the corresponding amphiboles, some authorities maintain that pyroxene and garnet are indicative of metamorphism under very high hydrostatic pressure. The rocks known as eclogite and griquaite are garnet-pyroxenites which some suppose to have been formed from gabbroic rocks in the deeper levels of the earth-crust. Boulders of griquaite (enstatite-garnet rock) and other pyroxenites are enclosed in the "blue-ground" of some of the diamond pipes near Kimberley, South Africa, but nothing is known of the conditions under which these rocks were formed.

Among the schistose rocks containing non-aluminous amphiboles, there is an anthophyllite-grunerite group, very rich in magnesia and iron, and a tremolite-actinolite group which has an appreciable content of lime in addition. These rocks are typically free from quartz and feldspar, and often consist almost entirely of amphibole, so the name amphibolite is more appropriate than schist. They consist for the greater part of interlocking needles and blades of one or more of the above amphiboles, sometimes forming radial groups. Associated minerals include talc and serpentine, probably formed by retrograde metamorphism of the amphiboles; also epidote, zoisite, and scapolite, representing original plagioclase; and accessory minerals such as ilmenite, rutile, apatite, and carbonates.

Serpentine is another fibrous rock, but the texture is so fine as to require microscopic study. The substance that we call serpentine exists in two forms, antigorite, which has a lamellar habit, and chrysotile, which is delicately fibrous. These two minerals are generally associated in massive serpentine. Common accessory minerals in serpentine are garnets of the pyrope variety, actinolite (often forming reaction rims round the garnets), talc, chlorite, magnesite, and chromite, spinel or ilmenite.

Talc schist is often associated with serpentine and may be formed by silicification and metamorphism of the latter. Talc-schist is a soft, silvery or greenish rock with a soapy feel, largely made up of scales and consequently highly cleavable, although there is also a massive, non-schistose variety that goes by the name of soapstone. The commonest accessory minerals in talc-schist are chlorite, actinolite or anthophyllite, and magnetite, but garnet is not uncommon. Rhombohedral crystals of dolomite or siderite may be present, forming a "talc-carbonate rock."

Genesis of metaluminous schists. Many serpentines and talc-schists are just altered peridotites and pyroxenites or hornblendites, and their eruptive origin is beyond doubt. Others may have a more complex history, with other metamorphic rocks as links in the chain of descent; but the subaluminous group of schists and gneisses as a whole is surely derived from the metamorphism of basic and ultra-basic igneous rocks and tuffs.

Peralkaline type.

The peralkaline group is a small and unimportant one. The jade of Burma, which is so highly valued as an ornamental stone in the east, is a rare, semi-translucent material made up of interlocking fibres of the mineral jadeite, $\text{NaAl}(\text{SiO}_3)_2$. Schists containing a soda-amphibole such as glaucophane (which differs from jadeite by holding some ferrous iron) are very uncommon. They have the appearance of ordinary hornblende-schists, but

under the microscope the amphibole shows a beautiful pleochroism from deep blue to purple and yellow. Pink garnets, green diopside and yellow epidote are common accessory minerals, along with biotite, quartz and calcite. Glaucophane-schists are known in Anglesey, on the islands of Syra and Milos in the Ægean Sea, in the Coast Range of California, and in the Japanese island of Shikoku.

According to the original definition of eclogite, this rock contains omphacite, a somewhat sodic pyroxene (acmite-diopside); it should therefore be referred to the peralkaline type. But in practice this omphacite-garnet rock has become confused with the enstatite-garnet rock (griquaite) of the Kimberley diamond mines, so the name eclogite has no specific value.

Genesis of peralkaline schists. A source in a peralkaline eruptive rock is indicated in some cases; in others, an argillaceous rock that has been enriched with soda (an adinole). The glaucophane schist of Angel Island, California, lies in a narrow strip between a cherty sandstone and a basic intrusive rock, and may have been generated by sodic solutions emanating from the latter.

SUGGESTIONS FOR READING.

- A. HARKER and J. E. MARR, *The Shap Granite and Associated Rocks*. Quart. Jour. Geol. Soc., 1891, p. 266.
- G. BARROW, *On an Intrusion of Muscovite-Biotite Gneiss in the South-Eastern Highlands*. Quart. Jour. Geol. Soc., 1893, p. 330.
- T. O. BOSWORTH, *Metamorphism around the Ross of Mull Granite*. Quart. Jour. Geol. Soc., 1910, p. 376.
- J. J. H. TEALL, *The Metamorphosis of Dolerite into Hornblende-Schist*. Quart. Jour. Geol. Soc., 1885, p. 133.
- J. S. FLETT, *The Geology of the Lizard*. Proc. Geologists' Assoc., 1913, p. 118.
- G. W. HAWES, *The Albany Granite and its Contact Phenomena*. Silliman's Journal, vol. 21, 1881, p. 21.
- F. F. GROUT, *Contact Metamorphism of the Slates of Minnesota by Granite and by Gabbro*. Bulletin Geol. Soc. of America, vol. 44, 1933, p. 989.

APPENDIX.

THE CHEMICAL ANALYSIS OF ROCKS.

Before committing himself to the delicate and time-consuming task of making a rock analysis, the petrologist should be clear about the purpose it is intended to serve, and whether it will contribute to the solution of his problem. If it seems unlikely that chemical analysis can add anything important to the study of the rock, then it is waste of time to undertake it. Too often, rock analyses are made merely as a concession to custom, and the resulting data are published without any discussion or any attempt to correlate the chemical with the mineralogical characters of the rock. The object of chemical analysis is to supplement the information afforded by the microscope; to achieve this object it is necessary to correlate the components indicated by the analysis with the phases identified under the microscope. Unless this is done, the work of the chemist is wasted.

To take an actual case: a certain rock was said to contain a plagioclase ranging in composition from Ab_1An_1 to Ab_1An_3 ; but a good chemical analysis showed that the average composition of this plagioclase was about Ab_3An_2 . In this case the petrographer was at fault, because he had studied only the best preserved pieces of a considerably altered feldspar. In another case of the same kind the plagioclase was said to be Ab_1An_1 , but chemical analysis indicated Ab_1An_4 . In the same rock the petrologist had reported 32 per cent. of biotite, yet the chemical analysis showed no excess of alumina over that required to form the normative feldspar. Putting these facts together it becomes clear that the chemist was at fault, having overestimated the amount of CaO . When this excessive amount of CaO was combined with alumina to form anorthite, it made the plagioclase appear too calcic and left no alumina for biotite.

These examples may serve to illustrate both the value of a good chemical analysis and the confusion that may be caused by a bad one. One of the advantages gained by making one's own analyses is that one can judge the accuracy of the work at every stage, and if any question of error should arise he knows where the error may lie. With an analysis made by another man no such judgment is possible.

Having resolved that a chemical analysis is needed for the solution of a petrographic problem, the petrologist must next decide whether to make a complete or a partial analysis. A complete analysis is always more satisfactory than a partial one, but if a partial analysis will suffice, one cannot be blamed for preferring it.

In an analysis of a silicate rock the following components should always be determined: silica, alumina, ferric and ferrous oxides, magnesia, lime, soda, potash, and water. It costs little more trouble to add titania and manganous oxide, both determined by simple colorimetric methods, and phosphoric oxide. In most rocks these twelve oxides are all that need be determined, but a few rocks contain significant quantities of carbon dioxide, chlorine, or sulphur. Many analysts make a practice of looking for traces of other components, especially zirconia, boric oxide, fluorine, lithia, baria, strontia, as well as nickel, copper, chromium, vanadium, and other heavy metals; but for *petrographic purposes* this is hardly ever necessary. It is interesting to know the distribution and relative abundance of these and other elements in rocks, but that is not the primary aim of petrology.

One cannot do more here than give the briefest possible outline of the procedure followed in rock analysis, in order to let the intending analyst know what he is undertaking and how he should apportion his time. By working off the minor operations during the long waits in the major ones one can save a good deal of time; but in a small laboratory the procedure is usually determined by the number of platinum utensils available. H. S. Washington found it possible to perform an analysis involving the determination of a dozen constituents in four to five days of eight or nine hours each, of course without interruption. Workers who have not got Dr. Washington's experience or his equipment may be well satisfied if they get the desired result in eight or ten days. Hurry is fatal to accuracy.

We shall assume that the reader is familiar with all the ordinary operations involved in gravimetric and volumetric analysis, and with the preparation of standard solutions.

Full particulars of the procedure should be sought in the following works, especially the first:—

H. S. WASHINGTON, *The Chemical Analysis of Rocks*. New York, 4th edition, 1930.

W. F. HILLEBRAND, *The Analysis of Silicate and Carbonate Rocks*. U.S. Geol. Survey, Bull. 700, 1919.

A. W. GROVES, *Silicate Analysis*. London, 1937.

H. A. FALES AND F. KENNY, *Inorganic Quantitative Analysis*, New York, 1939.

A. PREPARATION OF THE SAMPLE.

Take 25 to 100 grams, depending on coarseness of grain, of clean fresh rock splinters, avoiding weathered crusts. Crush bit by bit, by percussion, not by rubbing, in a hardened steel mortar till the powder passes through a sieve of about 90 mesh. Now take a fair sample of the powder and rub it down to the finest possible powder in an agate mortar. About five grams should be enough. Put this in a stoppered sample tube and keep it inside the balance case. Some of the coarser powder should be preserved in another sample tube; it may be used instead of the fine powder in the determination of certain minor constituents. (*Time, most of 1 day.*)

B. FUSION WITH SODIUM CARBONATE.

Use .5 to 1 gram of the finest powder. For a granite with low lime and magnesia it is advisable to use about 1 gram, but for a basic rock .5 to .7 gram is quite enough. Mix the powder thoroughly with ten to fifteen times its own weight of sodium bicarbonate (15 times in the case of a granite or other quartz-rich rock, 10 times for syenites, etc.). Transfer the mixture to a platinum crucible of capacity 30-40 CC. Set crucible in a clean silica triangle on the ring of a retort-stand, and cover with lid. Heat slowly over a small Bunsen flame to expel moisture, then gradually raise the temperature till fusion begins. Avoid rapid heating which would cause spattering. It is not necessary for the mass to become entirely fluid; it is better if it is merely fritted together. The necessary temperature is easily reached with a Bunsen burner, bringing the lower part of the crucible to a dull red heat. The entire operation requires about an hour. Finally lift the crucible with platinum-tipped tongs and set it on a clean stone slab to cool. (*Preparation and fusion, 2 hours.*)

C. TREATMENT OF THE MELT.

See that the crucible is perfectly clean outside. Lay the cold crucible on its side in a wide 500 or 600 CC. beaker and add distilled water up to about three-quarters of an inch. If there has been any spattering on to the lid, put it in the beaker too. Cover with a clock-glass. Add about 25 CC. of pure hydrochloric acid, a little at a time; if the solution turns pink, owing to formation of permanganate, add a few drops of alcohol. Solution is slow and may require some hours. When solution is complete except for flakes of silica, raise the crucible above the liquid by means of a stirring rod, wash it inside and out with a stream of water from the wash-

ing bottle, and remove the crucible. Do same with lid. Now transfer the contents of the beaker to a large platinum or fused silica basin, capacity 250 CC. Evaporate to dryness on the water bath and continue heating for some time after the residue appears to be dry. Now add 50 CC. of water and 5 CC. of hydrochloric acid; warm till all the soluble salts are dissolved. Filter through a 9 cm. paper. Wash with warm water holding about 5 per cent. of hydrochloric acid. Keep filtrate and washings. (*Time, most of 1 day.*)

D. TREATMENT OF SILICA PRECIPITATE.

When most of the moisture has drained off, transfer the filter and contents to a weighed 20 or 25 gram platinum crucible and dry in the hot-air oven. Then place the crucible on a silica triangle, with the lid on, and heat very slowly over a small flame to burn the filter paper. When all volatile organic matter has been destroyed, ignite for 15 minutes with the full heat of a Meker burner; remove to desiccator; cool in balance room for 15 minutes; then weigh. Repeat heating and weighing until weight is constant (W'). Now moisten the silica carefully with a few drops of water; add a few drops of 50 per cent. sulphuric acid, then about 5 CC. of hydrofluoric acid (using a small platinum crucible as measure). Bring to dryness (lid off) by careful heating over a small flame. Heat again for five minutes over the Meker burner, cool in desiccator, and weigh (W''). The difference, $W' - W''$, is silica. A further very small proportion of silica will be recovered later from the alumina precipitate. (*Time, about 4 hours.*)

Do not clean the crucible out, as the small residue in it belongs to the alumina group and must be weighed with the latter. (See F.)

E. PRECIPITATION OF ALUMINA, IRON, ETC.

To the filtrate from C. add about 10 CC. of concentrated hydrochloric acid, then add strong ammonia until the solution is nearly neutral. Heat nearly to boiling, then add more ammonia drop by drop until precipitation is complete and the solution is very slightly alkaline. (Test by withdrawing the stirring rod and touching a blue litmus paper with it.) Now add one or two drops of pure bromine to oxidize the manganese, and make sure that the liquid remains alkaline. Boil for a few minutes, then allow the precipitate to settle and filter as quickly as possible through an 11 cm. filter paper.

Wash precipitate with a hot 2 per cent. solution of ammonium chloride. Keep filtrate and washings. (See G.)

Redissolve the precipitate by running hot 1 : 2 hydrochloric acid through the paper, followed by hot water from the wash bottle. (It does not matter if a very little of the precipitate remains on the paper because the paper is to be kept for further treatment.) To the solution and washings add a little macerated filter paper, then reprecipitate exactly as before. Filter again, and add filtrate and first washings to the earlier filtrate. Wash with ammonium nitrate solution to remove chlorides. Keep the combined filtrates for the determination of lime and magnesia. (See G.). (*Time, $\frac{1}{2}$ to 1 hour.*)

F. TREATMENT OF THE ALUMINA GROUP PRECIPITATE.

The first filter paper from E. is ashed in the crucible that contains the residue from the silica. Meanwhile the second filter paper with its contents is allowed to drain; then it is dried in the hot-air oven, added to the ashes of the first paper in the crucible, and ashed slowly. Ignite over Meker burner for 15 minutes; cool in desiccator and weigh. Repeat the ignition and weighing until all carbon has been burnt off and the weight is constant (W). If necessary, the final heating may be done over a blow-pipe. The residue consists of Al_2O_3 plus Fe_2O_3 plus MnO_2 plus TiO_2 plus P_2O_5 (plus ZrO_2 plus Cr_2O_3 plus rare earths) plus a trace of silica. The ferric oxide, titania and silica are to be determined in this residue, but the other oxides are determined in separate portions of rock.

To the residue in the crucible add a few grams of powdered potassium-pyrosulphate (this must be prepared in advance and must not froth or spatter when melted). Heat gently over a very small flame and keep just melted, gradually raising the temperature till solution seems complete. This requires $\frac{1}{2}$ to 1 hour. Cool crucible on stone slab. When cold, lay the clean crucible on its side in a wide beaker; add some water and just 2 CC. of concentrated sulphuric acid. Warm till the cake is dissolved, then raise the crucible on a stirring rod, wash it outside and in with a stream of water from the wash bottle, and remove it. The empty crucible should now be heated and weighed and its weight subtracted from W (above) to get the weight of the group precipitate.

A few flakes of silica are generally seen in the filtrate and should be removed by filtering through a small filter paper. The small portion of silica so recovered should be treated exactly as described under D, and the weight added to the

main silica. (It is generally less than one-thousandth of the total silica.) (*Time, 3 hours.*)

The filtrate is kept for determination of ferric oxide and titania. (See J.)

G. PRECIPITATION OF LIME.

Bring the slightly ammoniacal filtrate from E to boiling. Meanwhile dissolve a few grams of ammonium oxalate in hot water, and add this to the filtrate, stirring all the time. Enough should be added to precipitate all the lime, but no great excess. Boil for a few minutes, then cover the beaker and let it stand overnight.

Filter through a 5 or 7 cm. paper; wash with water holding a little of the oxalate solution. Redissolve the precipitate by passing a small quantity of hot 1:1 hydrochloric acid through the paper, followed by hot water from the wash bottle. Reprecipitate the lime by adding ammonia in excess and a few drops of oxalate solution. Stand some hours or overnight. Filter and wash as before. Dry, ignite in 10 CC. platinum crucible, and bring to constant weight as CaO . (*Time of operation, 1-2 hours.*)

H. PRECIPITATION OF MAGNESIA.

To the filtrate from G add a tenth of its volume of ammonia. Dissolve a few grams of sodium-ammonium-phosphate in warm water, filter if necessary, and add to the cold solution with stirring. Set aside overnight or longer.

Filter, wash with water holding a little ammonia. Redissolve the precipitate in warm dilute hydrochloric acid and add a little of the phosphate solution. Now add ammonia drop by drop, with stirring, until there is a distinct excess. Stand several hours. Filter and wash with cold dilute ammonia. Ignite in 10 CC. platinum crucible over Bunsen burner. Weigh as $\text{Mg}_2\text{P}_2\text{O}_7$; this weight multiplied by .3621 equals MgO . (*Time of operation, 1-2 hours.*)

J. TOTAL IRON AND TITANIA.

(A) The solution from F should have a volume of about 100 CC. Pass hydrogen sulphide gas through it until the precipitated sulphur begins to coagulate ($\frac{1}{2}$ to 1 hour usually). Now filter into a large Erlenmeyer flask and pass hydrogen sulphide until a drop of the liquid gives only a very faint pink colour with a drop of KCNS solution on a white plate. Now

put in some scraps of platinum to promote boiling; insert tube from carbon-dioxide generator, start a rapid current of CO_2 , and bring the liquid to a boil. Continue boiling until the escaping vapour gives no dark colour to lead-acetate paper. Now cool the flask and contents as quickly as possible, keeping CO_2 passing all the time. When cold, titrate the iron with deci-normal potassium-permanganate (1 CC. equals .008 gram Fe_2O_3). (*Time, 2 hours.*)

(B) To determine titania, evaporate the liquid to less than 100 CC. Add 10 CC. of concentrated sulphuric acid. Cool, and filter into one tube of colorimeter. Fill a burette with standard titanium solution. In the other tube of the colorimeter put 50 CC. of water and 5 CC. of hydrogen-peroxide. To this add standard titanium solution drop by drop until the colour equals that due to iron in the unknown solution. Now read burette. Add 5 CC. of hydrogen-peroxide to the unknown solution and fill it up to the 100 CC. mark. Continue adding standard titanium solution to the second tube until the two colours are identical, both tubes being then at the 100 CC. mark. Read burette again; calculate TiO_2 from amount of standard solution used. (*Time, $\frac{1}{2}$ hour, excluding evaporation.*)

K. FERROUS OXIDE.

Boil three lots of about 250 CC. each of water in wide beakers, and pass CO_2 through them while cooling. Also add to each about 5 CC. of sulphuric acid and five grams of solid boric acid. Weigh out three lots of the rock powder on separate watch glasses, about .5 to .8 gram on each. Fill a burette with decinormal potassium permanganate; also prepare a small quantity of warm 1 : 1 sulphuric acid. Put about 20 CC. of water in a large platinum crucible; mount it on a retort stand over a Bunsen burner, and find by trial the height of the flame which will just keep the water simmering when the lid is on the crucible. Practise judging this by ear.

When everything is ready, put the first portion of rock in the crucible, add some platinum scrap, moisten the powder with water, add 10 CC. of warm 1 : 1 sulphuric acid, then 5 CC. of hydrofluoric acid (measured in a small platinum crucible). At once place the crucible in position on the retort stand, with the lid tightly on, and heat quickly until the liquid can be heard simmering. Keep it simmering for about five minutes. Bring up the first beaker of boiled-out water; seize the crucible and lid with tongs and plunge them into beaker. Remove the tongs and titrate the liquid as quickly as possible to the first pink blush that persists for a few moments in spite

of energetic stirring. Do not try for accuracy at the first attempt but just get an approximate value for the quantity of permanganate solution needed. Remove the crucible from the beaker, clean it out, and examine the residue for undecomposed grains of iron-bearing minerals. Repeat the operation with the second portion of powder, giving longer time if solution was incomplete in the first case. This time, knowing roughly how many CC. of permanganate solution are needed, add nearly the whole of this in one stream; then stir vigorously until the colour is discharged, and continue adding permanganate drop by drop until the exact end point is reached. The third attempt will give a useful check on the second. Take the best result of the three, not the average. 1 CC. decinormal permanganate equals .0072 gram FeO . This amount must be calculated into Fe_2O_3 , and deducted from the total Fe_2O_3 found in paragraph J, in order to get the true amount of Fe_2O_3 in the rock. (*Time, after all preparations have been made, 10 minutes for each determination.*)

L. MANGANOUS OXIDE.

It is not usually necessary to determine this oxide except in iron-rich rocks. Weigh out about 1 gram of the coarser powder into a small platinum basin, add some concentrated nitric acid and 5 CC. of hydrofluoric acid. Evaporate to dryness on a water bath. Add more nitric acid and evaporate again; repeat evaporation three or more times. Now add just enough 50 per cent. sulphuric acid to moisten the solid crust, then heat on the sand bath or over a direct flame until the crust is dry—but do not heat so strongly as to decompose the sulphate. Take up in hot water and filter. To the filtrate add at least 10 CC. of concentrated sulphuric acid and from a quarter to half a gram of solid potassium periodate. Boil and keep hot till the purple colour of permanganate appears, then cool and transfer to a measuring flask the capacity of which will depend on the intensity of the purple colour.

A measured quantity of the standard manganese solution is put in a beaker and treated with acid and periodate exactly as above. (Alternatively, decinormal permanganate may be diluted to a suitably pale colour and used as the standard without further treatment.) The standard solution is then put in a burette and the unknown (or a measured fraction of it) in one tube of the colorimeter. The standard is run into the other tube until the colours match, both tubes being then at 100 CC. (*Time, most of 1 day.*)

M. PHOSPHORIC OXIDE.

Take one gram of the coarser powder in a small platinum basin. Moisten with water, add 10 CC. of concentrated nitric acid and 5 CC. of hydrofluoric acid. Evaporate to dryness on the water bath. Add more nitric acid and dry again; repeat this once more, and then dry completely. Warm up with dilute nitric acid, filter, and wash with the same acid. To the filtrate add about 25 CC. of standard ammonium nitrate solution (Washington, 34 per cent.) and bring nearly to the boil. In a small beaker put 20 CC. of 25 per cent. nitric acid and the same quantity of standard ammonium molybdate solution (30 grams in 500 CC. of water). Warm but do not boil this liquid, and add it to the unknown. Let stand overnight.

Filter. Wash with a mixture of ammonium nitrate solution, nitric acid, and water in equal parts. Redissolve the precipitate in 1:1 ammonia. To the solution add 10 CC. of filtered magnesia mixture (Washington p. 62). Let stand overnight. Filter. Wash with weak ammonia. Carbonize and ignite in small platinum crucible over Bunsen flame. Weigh as $Mg_2P_2O_7$, which multiplied by .638 equals P_2O_5 . (Time, 1 day and 1 hour.)

N. WATER.

Water given off below 110° (H_2O —) is determined by weighing about 1 gram of the fine powder in a watch glass. Heat in air oven for half an hour, cool in desiccator, weigh quickly. Repeat to constant weight. (The powder can be used for the MnO or P_2O_5 determination.)

Total water may be determined by ignition of the powder in a platinum crucible, provided that the rock is a leucocratic one and contains no olivine or carbonates. Otherwise total water must be determined by the Penfield method (see Washington), preferably the modified form devised by C. O. Harvey.

An ignition tube of very hard glass, conveniently measuring about 13 cm. by 1.5 cm., and closed at one end, is encircled at the open end by a 20-24 mm. rubber stopper. A small glass weighing bottle fits on to this stopper, and a very narrow escape tube passes back from the weighing bottle through the stopper to a guard-tube filled with calcium chloride. The ignition tube is held horizontally by the clamp of a retort-stand, and a platinum boat, containing the weighed rock-powder, is pushed down to the closed end of the tube. A few grams of prepared calcium chloride are put in the weigh-

ing bottle, which is then weighed with its glass cap on. Now the cap is removed and the weighing bottle is fitted tightly on to the rubber stopper at the end of the ignition tube, with an asbestos shield to protect it from heat. The powder in the ignition tube is now heated as strongly as possible with a large Bunsen or Teclu burner, and the escaping water vapour condenses or is absorbed in the weighing bottle (which may be kept cool with strips of wet blotting-paper hung on it). After 15 or 20 minutes the weighing bottle is detached, at once closed with its glass cap, dried on the outside, and allowed to cool in the balance case before weighing. This method is much simpler than the original method of Penfield, and it gives excellent results. (For the original description see Geol. Survey of Great Britain, Bulletin no. 1, 1939, p. 8.) (*Time, 1 hour.*)

O. ALKALIES.

Use about half a gram of very finely ground powder. Mix it in a platinum basin with .7 gram of powdered ammonium chloride. Weigh accurately about 4 grams of CaCO_3 (alkali content known). If chemically pure calcium carbonate is available it is not necessary to weigh accurately. Put a little of the carbonate in the bottom of the large platinum crucible; mix the remainder with the rock powder and ammonium chloride, taking care to ensure intimate mixing. Transfer the mixture to the crucible and cover with lid. Heat over a small flame till no more ammonia fumes are given off (20 minutes). Then heat crucible to *low* red heat over Bunsen flame for about 40 minutes. Cool on stone slab. Place the crucible in a large silica basin, half fill the crucible with water, also put some water in the basin and let it stand on the water bath for some time. When the disintegration of the cake seems complete, wash the contents of the crucible out into the basin; wash crucible and remove it. Dilute the liquid considerably and decant it through a filter. Rub the powder remaining in the basin with an agate pestle, add hot water and decant again. Repeat this several times till all the powder has been transferred to the filter. Finally, wash with 200 CC. of hot water.

Wash the powder from the filter paper back into the basin. Dissolve it in hydrochloric acid and see if there is any unattacked residue of silicates. If not, then proceed as follows.

To the filtrate add ammonia and bring it to the boil. Dissolve 2 grams of ammonium carbonate in cold water. Add

enough of this to the solution and continue boiling for a few minutes. Filter again, and catch the filtrate in the 250 CC. platinum basin. Wash till the washings show no chlorine reaction.

Evaporate to dryness and continue heating until the crust is entirely white and opaque. Cover with a clock glass and dry in the air oven. Now drive off ammonium salts with extreme care, using a direct flame held in the hand and kept moving. Take up the residue with a little water. (If the rock contains sulphur or SO_3 , these must now be removed by addition of a single drop of BaCl_2 , which is then removed by a few drops of ammonium carbonate.) Add a few drops of ammonium oxalate and evaporate almost to dryness. Take up in a little water and filter through a very small funnel into the weighed 50 CC. platinum basin. Wash with water till a single drop gives no chlorine reaction. Add a drop of hydrochloric acid to the liquid in the basin, evaporate again to complete dryness on the water bath, and finish drying in the hot-air oven.

Again drive off small residue of ammonium salts, heating till the alkali chlorides just begin to melt. Cool the basin in a desiccator and weigh the alkali chlorides quickly. (From this weight deduct the weight of NaCl in the CaCO_3 .)

Now dissolve the chlorides in 5 CC. of water. A few flakes of carbon may be seen but may be neglected. If any lime salts remain, it will be necessary to filter, evaporate, and weigh again.

Now add the appropriate quantity of chloroplatinic acid. For every .1 gram of combined chlorides it is necessary to add .168 gram of platinum metal. Evaporate on a slowly boiling water bath till the liquid is thick and solidifies on cooling. When cold, add a few CC. of alcohol of specific gravity .86. Break up the yellow crust with a stirring rod and decant the liquid through a very small filter. Repeat this several times until the alcohol comes away colourless. Before taking the next step, it is advisable to let the filter paper and the contents of the basin stand until all the alcohol dries off. Any grains of potassium chloroplatinate on the filter paper must now be washed back into the basin with hot water. Evaporate the contents of the basin to dryness and finally heat in the air bath for half an hour at 125° . Weigh as potassium chloroplatinate. This weight multiplied by .1938 equals K_2O . The same weight multiplied by .307 equals KCl . Total chlorides minus KCl equals NaCl . NaCl multiplied by .5303 equals Na_2O . (Time, to weighing of chlorides, 6-8 hours; chloroplatinate operation, add 3 hours.)

P. ALTERNATIVE TREATMENT OF ALKALI CHLORIDES.
(Method of F. Walker.)

After weighing mixed chlorides, dissolve in a little water and transfer to a small beaker. Add five drops of 4 per cent. potassium chromate solution and titrate with $N/50$ silver nitrate solution against a pure white background. For comparison, put in another beaker a few CC. of NaCl solution, add five drops of 4 per cent. potassium chromate and then enough silver nitrate to give a bulky white precipitate, but not enough to form any pink silver chromate.

By comparing the two beakers, during the titration of the chlorides the change from pure white or faint yellow to pale salmon pink is easily observed.

From the ratio of chlorine to combined chlorides, the ratio of NaCl to KCl may be deduced.

INDEX.

- Actinolite, 25, 189
 Adamellite, 57, 67
 Adamello, 71
 Adirondack Mts., 16, 84
 Ægirine, 25, 122
 Agglomerate, 165
 Akerite, 84, 91
 Alabaster, 161
 Alban Hills, 125
 Alberta, 121
 Albite, 23
 Aletsch, 16
 Alkali-granite, 58
 Alkali-lime granite, 58
 Allanite, 31
 Allivalite, 104
 Allophane, 136
 Almandine, 29, 188
 Almunge, 94
 Alnø, 126
 Alum-shale, 177
 Amphibole, 25
 Analcime, 29, 120, 128
 Andalusite, 187, 200
 Andesine, 24
 Andesite, 84, 85, 90, 98
 Andradite, 29, 188
 Angel I., 217
 Anglesey, 214
 Anhydrite, 139, 158
 Anorthite, 23, 187
 Anorthosite, 84, 86, 87, 97
 Anthophyllite, 25, 189
 Anthracite, 149
 Apache Mts., 128
 Apatite, 32
 Aplite, 40
 Aragonite, 138, 144
 Arfvedsonite, 26
 Arkose, 169, 170
 Ascension, 77
 Astrophyllite, 32
 Augite, 25
 Augite-andesite, 79, 98
 Auto-metamorphism, 65, 68
 Auvergne, 93, 112, 128
 Bahia, 153
 Bancroft, 84, 118
 Banket, 168
 Barr-Andlau, 202
 Basalt, 81, 84, 87, 90, 99, 102, 103
 Batholith, 17, 18, 19, 61
 Bearpaw Mts., 129
 Bedding-plane, 130
 Bentonite, 177
 Berkhamstead, 209
 Beverley, 84, 94
 Bex, 159, 165
 Bill Williams Mt., 96
 Biotite, 27
 Blairmorite, 120
 Blue Ridge, 70
 Bodenmais, 208, 211
 Bone-breccia, 146
 Borolanite, 124, 127
 Boss, 17
 Boulder, 60
 Boulder-clay, 165
 Bowen-Andersen effect, 89
 Breccia, 163, 166
 Brucite, 189
 Brünn, 96
 Bushveld, 16, 97, 100
 Bulawayo, 84
 Bull Mt., 208
 Bullfrog, 77
 Butte, 35
 Bytownite, 24
 Calcareous tufa, 151

- Calcite, 138, 142, 144
 Calcrete, 154
 Calc-sinter, 151, 153
 Caliche, 162
 Canary Is., 112, 129
 Cancrinite, 28, 120
 Canobolas Mts., 95
 Cape Town, 186
 Carnegieite, 24
 Carpathians, 72, 76
 Celsian, 23
 Cevadaes, 126
 Chalcedony, 31, 138
 Chalk, 152
 Chamosite, 137, 155
 Charnockite, 70, 72, 214
 Chert, 157
 Chiastolite, 187
 Chlorite, 137, 189
 Chloritoid, 188, 208
 Chloropal, 136
 Christiania, 94, 201, 203
 Christmas I., 147
 Chrysophyre, 113
 Clay, 175
 Claystone, 174
 Clay-silicates, 136
 Clino-amphibole, 26
 Clino-enstatite, 25
 Clino-pyroxene, 25
 Clipperton atoll, 147
 Coal, 148
 Colloids, 134
 Colorado, 74
 Colour-index, 52
 Colour-ratio, 52
 Columbia River, 87
 Conglomerate, 167
 Cordierite, 187
 Corndon, 16
 Cornwall, 69
 Corundum, 31, 109, 208
 Corundum-pegmatite, 106, 107, 109
 Crawford Notch, 202
 Crush-breccia, 182
 Crush-conglomerate, 197
 Cryptocrystalline, 11, 66
 Crystalline schist, 179, 184, 206
 Crystallinity, 14
 Cuillin Hills, 112
 Current-bedding, 132
 Cyanite, see kyanite
 Dacite, 59, 77
 Daly's hypothesis, 117
 Deccan, 87, 99
 Dedolomitization, 204
 Diabase, 79, 80, 81, 90, 98
 Diallage, 97
 Diaspore, 138
 Diatomaceous earth, 147
 Differentiation, 13, 15, 17, 20
 Diopside, 25
 Diorite, 79, 80, 81, 83, 85, 95, 96
 Dolerite, 80, 81, 86, 90, 98
 Dolomite, 138, 145
 Drachenfels, 93
 Dreikanter, 135
 Duluth, 16, 17, 86, 104, 112
 Dun Mt., 113
 Dunedin, 95, 129
 Dungannon, 110
 Dunite, 113, 114
 Duppau, 128
 Durbach, 92
 Dyke, 12, 13
 Dyke-rocks, 9, 13, 38
 Dyscrystalline, 52
 Eclogite, 212
 Eifel, 112, 129
 Ekaterinburg, 214
 Elaeolite-syenite, 115
 Electric Peak, 72, 96
 Elkhead Mts., 129
 Emplacement, 19
 Enstatite, 25
 Epidote, 30, 189
 Essex Co., 127
 Essexite, 127
 Eucolite, 32
 Eudialyte, 32
 Eucrystalline, 52
 Extrusive rocks, 9
 Eyed-gneiss, 186, 206
 False-bedding, 132
 Faroe Is., 99

Fars series, 159
 Fault-breccia, 164, 197
 Fayalite, 28
 Felsite, 73
 Feldspar, 23
 Feldspathoids, 29
 Fen district, 127
 Fergusite, 123
 Ferricrete, 157
 Fifeshire, 75
 Flint, 157
 Flinty crush-rock, 198
 Flocculation, 134
 Flow-breccia, 166
 Fluorides, 32
 Fluorspar, 32
 Fluosilicates, 32
 Forfarshire, 207, 209
 Forsterite, 28, 189
 Foya, 117, 125, 126
 Foyaite, 117, 126
 Franspoort, 126
 Fugitive constituents, 14
 Funafuti, 145
 Gabbro, 79, 80, 83, 86, 95
 Gabbrodiorite, 83
 Gallatin Co., 209
 Garabal Hill, 100
 Garnet, 29
 Geyserite, 157
 Gibbsite, 138
 Glamorgan, 100
 Glasshouse Mts., 95
 Glaucinite, 137, 156
 Glauconite, 25, 124
 Globe, 77
 Gneiss, 61, 184, 204
 Graded bedding, 132
 Gran, 100
 Granitberg, 126
 Granite, 57-71
 Granitic texture, 66
 Granodiorite, 58, 59, 68
 Granophyre, 73
 Granularity, 14
 Granulite, 205
 Graphitic granite, 64
 Graywacke, 169
 Great Basin, 77

Great Dyke, 100, 105
 Great Rift Valley, 95, 128
 Great Serpentine Belt, 105
 Greenland, 117, 121, 126, 127
 Griquaite, 215
 Grit, 169
 Grossularite, 29, 188
 Grünerite, 25
 Guano, 146
 Guildford, 211
 Gunildrud, 201
 Gypsum, 139, 158

Haliburton, 118
 Halloysite, 136
 Hanover, 148
 Harzburgite, 113
 Hastingsite, 26
 Hatüyne, 28
 Hawaii, 105, 111, 112, 113
 Hebrides, 112, 181, 198
 Hedenbergite, 25
 Hematite, 31
 Henry Mts., 15
 Highwood Mts., 15, 119, 123
 Hillsborough, 159
 Hornblende, 26
 Hornblendite, 88, 99
 Hornfels, 179
 Hornstone, 179, 182, 193, 200
 Hydro-mica, 137
 Hypersthene, 25

Iceland, 76, 99
 Idaho batholith, 61
 Ijolite, 126, 127
 Ile de Groix, 208
 Ilmausak, 126
 Ilmen Mts., 110
 Ilmenite, 31
 Injection-gneiss, 61, 186
 Insizwa, 104
 Inset, 11, 66
 Intrusive rocks, 9, 12
 Ironstone, 155
 Iron Pyrites, 32, 139
 Isle of Man, 182
 Isomorphism, 22
 Italite, 124, 125
 Itatiaya, 117

- Jacupirangite, 126
 Jadeite, 25, 216
 Jasper, 138, 157
 Java, 118
 Joints, 14, 132

 Kaiserstuhl, 128, 129
 Kaliophilite, 29
 Kaolinite, 136, 174
 Karroo, 86, 98
 Katzenbückel, 128
 Kauaiite, 111
 Kentallen, 110
 Kieselguhr, 148
 Kimberlite, 12, 106, 114, 166
 Kinta, 209
 Kinzigite, 209
 Kola, 84, 94, 117, 123, 126
 Kuusamo, 127
 Kyanite, 187
 Kyschtym, 110

 Labrador, 86
 Labradorite, 24
 Laccolith, 15
 Lake Lahontan, 153
 Lamination, 131, 132
 Lamprophyre, 40
 Laterite, 175
 Laurvik, 94
 Lava, 9, 10
 Lepidolite, 26
 Lepidomelane, 26
 Leucite, 29, 118, 119, 121, 123
 Leucite Hills, 119, 125
 Leucite-phonolite, 124
 Leucite-tephrite, 125
 Leucitite, 125
 Lignite, 148
 Lime diorite, 83
 Lime-gabbro, 83
 Limestone, 142, 202
 Limonite, 138
 Lipari Is., 76
 Liparite, 76
 Litchfield, 209
 Lithophysæ, 67
 Littleton, 209
 Lizard, 112
 Loch Borolan, 107, 110, 124

 Loess, 135, 172
 Lopolith, 16, 19
 Lujaurite, 123, 126

 Madeira, 112
 Madras, 70, 72, 180, 198
 Madupite, 125
 Magma, 9
 Magma-type, 47
 Magmatic differentiation, 20
 Magnet Cove, 123, 124, 127
 Magnetite, 31
 Malignite, 126
 Manhattan, 213
 Marble, 183, 204
 Marcasite, 139
 Mariut, 145
 Marmorite, 183, 200, 204
 Marysville, 72
 Melanite, 29, 107, 109, 122
 Melilite, 30, 107, 109
 Melilite-basalt, 107, 114
 Metaluminous type, 50
 Metaluminous schists, 165, 176
 Metamorphic facies, 194
 Metamorphic grade, 195
 Metasilicates, 25
 Miask, 127
 Mica, 27
 Microcline, 23, 24
 Micropegmatite, 64, 67
 Microperthite, 24
 Migmatite, 61, 183, 186
 Milos, 217
 Missouri, 107
 Missouriite, 119, 123
 Mode, 45
 Monazite, 32
 Mt. Cimini, 110
 Mt. Flinders, 95
 Mt. Pelée, 65
 Mt. Shasta, 77
 Mt. Vesuvius, 119, 166
 Monteregean Hills, 92, 110
 Montmorillonite, 136
 Monzonite, 79, 80, 81, 84, 85,
 89, 91
 Morelos, 203
 Mudstone, 177
 Mugarite, 111

- Muscovite, 27
 Mylonite, 180, 198

 Nandewar Mts., 94
 Napoleonite, 80
 Nepheline, 28, 118
 Nepheline-syenite, 95, 119
 Nepheline-tephrite, 129
 Nephelinite, 128
 New South Wales, 105
 Nontronite, 136
 Nordmarkite, 92
 Norite, 79, 86, 95, 97
 Norm, 45
 Nosean, 28

 Oahu, 113
 Obsidian, 74, 76
 Oil-shale, 148
 Oligoclase, 24
 Oligoclasite, 80
 Olivine, 28, 89, 105, 108
 Olivine-basalt, 102, 105, 112
 Olivine-gabbro, 104, 112
 Olivine-leucite, 124
 Olivine-norite, 104, 111
 Olivine-tephrite, 124
 Ontario, 84, 92, 107, 109
 Onyx-marble, 153
 Oolite, 151, 153, 155
 Opal, 31, 138
 Ophitic texture, 90
 Orange Free State, 180, 198
 Ortho-amphibole, 26
 Orthoclase, 23
 Ortho-pyroxene, 25
 Oslo, see Christiania
 Ottrelite, see Chloritoid
 Overgrowths, 23
 Overhand stoping, 19
 Oversaturated rocks, 50, 57
 Oxides, 31

 Palisades, 87, 105
 Pantelleria, 76
 Pantellerite, 76
 Parallel texture, 66
 Parana, 87
 Peat, 148
 Pectolite, 122

 Pegmatite, 14, 40, 64
 Peralkaline type, 51
 Peralkaline schists, 195, 213
 Peraluminous type, 51
 Peraluminous schists, 195, 206
 Periclase, 189
 Peridotite, 104, 105, 106, 113
 Perknite, 84, 88, 99
 Perlite, 73
 Perovskite, 32
 Persia, 159, 160
 Perthite, 24
 Phacolith, 16
 Phenocryst, see Inset
 Phlogopite, 27
 Phonolite, 115, 119, 124
 Phosphates, 32
 Phosphorite, 146
 Phyllite, 177
 Picrite, 112
 Picrite-basalt, 113
 Pigeonite, 25
 Pigeon Point, 112
 Pilansberg, 85, 117, 126, 128
 Pinite, 137, 208
 Pipe, 12, 106
 Pisolite, 153
 Pitchstone, 73, 75
 Plagioclase, 24
 Platinum, 106
 Plauen, 64, 83, 84, 92
 Pleonaste, 188
 Plumas Co., 110
 Pluton, 17, 20
 Plutonic rocks, 9
 Poikilitic texture, 108, 123, 200
 Poohbah Lake, 107, 110
 Porphyritic texture, 11, 66
 Porphyry, 40
 Potash-albite, 23
 Potash-nepheline, 29
 Premier Mine, 12, 106
 Pretoria, 93, 156
 Pseudo-leucite, 120, 123, 124
 Pseudo-tachylyte, 180, 198, 199
 Purcell Mts., 72
 Pyrite, 32
 Pyrope, 29, 109
 Pyroxene, 25
 Pyroxenite, 88, 99

- Pyrrhotite, 32, 139
 Quartz, 31, 63, 64
 Quartz-diorite, 57, 58
 Quartzite, 170, 199, 200
 Quebec, 86
 Quincy, 71, 84, 94
 Radiolarian earth, 147
 Rapakiwi, 65
 Rauchwacke, 154
 Rhodonite, 25
 Rhyodacite, 59, 74, 77
 Rhyolite, 59, 74, 75, 76
 Riebeckite, 26
 Ripple-mark, 133
 Ripple-mark index, 133
 Rockall, 2, 71
 Rockallite, 2
 Rock flour, 136, 163
 Rock magma, 9
 Rock rot, 136, 163
 Rock salt, 139, 161
 Rock species, 37
 Rock type, 37
 Roman region, 117, 121, 128
 Ross of Mull, 209
 Rum, 104, 112
 Saganaga, 70, 93, 96, 100
 Saguenay, 86
 St. Austell, 69
 St. Gotthard, 16, 207, 209, 212
 St. Hilaire Mt., 110
 St. Thomas' Mt., 70
 Salcrete, 162
 Salem, 180
 San Andreas, 181, 200
 Sandstone, 131, 133, 170
 San Francisco dist., 75, 99
 Santorin, 78
 Sardinia, 94
 Sark, 96
 Saturated rocks, 50, 79
 Scapolite, 188
 Schist, 179, 184, 186, 195, 204
 Sekukuniland, 127
 Sepulchre Mt., 96
 Sericite, 137, 175
 Serpentine, 105, 108, 113, 138, 189, 213
 Serra de Itaquí, 210
 Serra de Monchique, 126
 Serra de Tingua, 128
 Shale, 177
 Shevaroy Hills, 72
 Shiant Isles, 105
 Shikoku, 217
 Shonkinite, 84, 91
 Shonkin Sag, 15
 Siderite, 138
 Siebengebirge, 93, 112
 Sierra Leone, 104, 112
 Sierra Nevada, 112
 Sieve-structure, see Poikilitic
 Silcrete, 157
 Silica group, 31
 Siliceous sinter, 157
 Sill, 12, 13, 19
 Sillimanite, 187
 Siltstone, 172
 Silver Peak, 77
 Skarn, 204
 Skye, 111, 112
 Slate, 177
 Smalingen, 110
 Snake River, 99
 Snowbank, 84
 Soda-amphibole, 26
 Soda-anorthite, 24
 Soda-diopside, 25
 Soda-diorite, 83
 Soda-gabbro, 83
 Sodalite, 28, 116, 119, 120
 Soda-orthoclase, 23
 Solid solution, 22
 Sölvserget, 203
 Souffrière, 78
 Spessartite, 29
 Sphene, 32, 122
 Spherulites, 11, 66, 154
 Spherulitic texture, 11
 Spinel, 31, 188
 Stassfurt, 158, 162
 Staurolite, 188
 Stillwater, 100
 Stock, 17
 Stopping, 19
 Subaluminous type, 51

- Subaluminous schists, 195, 211
 Sudbury, 16, 17, 86
 Sulphides, 32
 Sviatoy Noss, 107, 110
 Syenite, 84, 91
 Syra, 217

 Tabankulu, 104, 112
 Talc, 189
 Talc-carbonate rock, 216
 Tephrite, 124, 125
 Theralite, 126, 128
 Tillite, 163, 165
 Tinguaita, 128
 Titanates, 32
 Titanite, see Sphene
 Titanomagnetite, 31
 Titanosilicates, 32
 Tonalite, 57, 67, 71, 72
 Tonopah, 77
 Topaz, 32
 Torbanite, 150
 Tourmaline, 27
 Trachyandesite, 84, 93
 Trachyte, 84, 90, 93
 Trap-shotten gneiss, 180, 199
 Tremolite, 25, 189
 Tridymite, 31, 64
 Troctolite, 112
 Tschermak's silicate, 25
 Tuff, 9, 165
 Turgite, 155
 Tyrol, 210

 Umptek, 94
 Undersaturated rocks, 50, 102, 115
 Upsala, 84
 Ural Mts., 106, 110, 208, 214

 Varves, 176
 Vermilion, 60, 61, 62, 93, 95, 100
 Vesuvianite, 188
 Virginia, 98, 208
 Vitrophyre, 73
 Volcanic conglomerate, 169
 Volcanic bombs, 166
 Volcanic rocks, 9

 Wedge, 12
 Wedgedyke, 12
 Whin Sill, 98
 Wicklow Hills, 61, 65
 Witwatersrand, 168
 Wollastonite, 25, 184, 189

 Xanthosiderite, 155
 Xenotime, 32

 Yellowstone Park, 76, 96, 153

 Zambezi, 168
 Zeolites, 137
 Zircon, 32
 Zirconosilicates, 32
 Zoisite, 30, 189

